# Assessing the value of ecological intensification in improving smallholder farmers' food security and rural livelihoods in a changing climate

**FARIRAI RUSERE**

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# DECLARATION INCLUSION OF PUBLICATIONS

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SIGNATURE: Signed by candidate DATE: 30/06/2019

STUDENT NAME: FARIRAI RUSERE STUDENT NUMBER: RSRFAR001

# SUPERVISOR

Dr. Olivier Crespo

Never give up a dream just because of the time it takes to accomplish it.

# ABSTRACT

Attaining the twin goals of food security and environmental sustainability has spurred focus on two main models of production, sustainable and ecological intensification as means to produce more food per unit land area while simultaneously ensuring environmental sustainability. A better understanding of their suitability and applicability in diverse and heterogeneous biophysical and socio-economic situations of smallholder farmers is still largely needed in sub Saharan Africa (SSA). This study aimed to assess the value of ecological intensification of agriculture to improve food production systems and environmental sustainability in smallholder farming systems in the face of climate variability and change. This study uses two rural districts in South Africa namely Vhembe and Amathole from Limpopo and the Eastern Cape provinces respectively as a case study to explore how ecological intensification can help smallholder farmers. The study explored the fit and potential of ecological intensification in smallholder agricultural systems and steps to be taken to support its implementation and development. The study then uses the Design, Explain, Evaluate and Design (DEED) approach to develops pathways relying on ecological intensification technologies and suiting different farm types of smallholder agriculture. Two iterations of the DEED approach were performed that enabled characterisation of farmers and farming systems and farming systems analysis of challenges and constraints that helped to identify and link specific ecosystem services with suitable ecological intensification options. Furthermore, the study assesses the acceptance and use of ecological intensification options in the heterogeneous biophysical and socioeconomic context of smallholder farmers through the Unified Theory of Acceptance and Use of Technology (UTAUT) framework. Besides the productivity potential, the study sheds light on locally relevant knowledge that must be considered to enable acceptance and use of ecological intensification options. I finally explored the potential of ecological intensification to meet the goals of improving productivity and environmental sustainability concurrently through a biophysical modelling approach encompassing a farm typology, a crop model and a farm focussed greenhouse gas calculator. The results provide valuable insights into the ongoing debate on how to intensify smallholder cropping systems. More specifically, the results show that the integration of agroecological approaches in smallholder cropping systems has the potential to deliver ecological intensification in which productivity is improved and ecosystem services such as climate change regulation through reduction of GHG emissions from cropping systems are simultaneously increased to enhance environmental sustainability. Overall, the study articulates various pieces of evidence to show that ecological intensification is suitable, applicable and, can attain the twin objectives of improving food production systems concurrently ensuring environmental sustainability, in heterogeneous smallholder agricultural systems in SSA. This contribution raises the need for further attention to be given to smallholder agricultural intensification policies and research or to agricultural intensification to explicitly consider the heterogeneous biophysical and socioeconomic circumstances of smallholder farmers in SSA.

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# DEDICATION

To my late father Hamilton C. Rusere, thank you for introducing me to the world of agriculture

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

This chapter sets the scene for the PhD thesis by providing an overview of the leading themes of this thesis. Firstly, it reveals the current and projected world population growth, narrowing to population growth in rural areas of sub Saharan Africa (SSA). It then highlights the importance of rainfed agricultural systems particularly for food security and livelihoods in rural SSA. Furthermore, it then presents the current food security situation in SSA. It also presents the challenges posed by rapid population growth and climate variability and change on food security in rural SSA. This chapter then explores the potential and limitations of cropland area expansion consequently advocating for agricultural intensification as a sustainable alternative to meet the increased demand for food to achieve food security in rural SSA. The chapter gives a brief background of conventional approaches to agricultural intensification, their limitations and lack of fit with the biophysical and socio-economic context of rural low input smallholder farming communities in SSA. It introduces two approaches to intensify smallholder agricultural systems that are being debated globally while highlighting the research gaps that must be addressed to see their value in SSA. Ultimately, the chapter then motivates the PhD focus on ecological intensification, leading into the research question, aim and consequent objectives of this thesis, the methods, and tools used to achieve the objectives and an outline of the thesis structure.

## 1.2 Population growth, livelihoods and poverty in SSA

Global change due to rapid and enormous population growth remains a critical challenge in the twenty-first century (Hertel, 2015). By 2050, 9 billion people are expected to be living in this world due to rapid population growth (Population Reference Bureau, 2018). In sub Saharan Africa (SSA), enormous and rapid growth in population is expected to occur. Currently, SSA has about 900 million people, a number expected to nearly double to 1.4 billion by 2030 (Thomas & Zuberi, 2012; United Nations, 2013). Africa as a continent is predominantly rural, with livelihoods highly dependent on rainfed agricultural systems. About 65 % of employment is derived from the agricultural sector and agricultural related activities. Many rural areas of SSA are associated with high population densities and the rural population is expected to further increase (Cleland & Machiyama, 2017). Rural areas are associated with widespread poverty, low income levels, minimum educational levels, low agricultural productivity, malnutrition, hunger and food insecurity (Vermeulen et al., 2012). A drastic rise in the rural population will likely exacerbate poverty, inequality, malnutrition, hunger and make achieving food security even more difficult. Thus, there is increased concern of further population growth impacts particularly population density growth in these areas where most people rely on rainfed agricultural systems and ecosystem services for livelihoods.

## 1.3 Food security situation in SSA

Food security has remained a challenge in SSA (Conceição et al., 2016). The Food and Agricultural Organisation (FAO) recently estimated that one in every four people in Africa, do not have adequate and decent food and nutrition for a healthy life (FAO, 2018). Furthermore, Africa continues to lag in terms of reducing malnutrition and chronic hunger. According to FAO (2018), SSA currently has the largest proportion of food insecure people (925 million), and 795 million people remain undernourished and the proportion of food insecure people is expected to increase concurrently with the rapidly growing population in SSA (UNDP, 2015). Despite improvements made in other continents over the last 25 years in improving essential nutritional necessities of the disadvantaged, vulnerable and poor, in Africa undernourishment and food insecurity is still a serious problem (FAO, 2018). This is despite the fact that much of the food in Asia and Africa is produced by smallholder farmers (Ricciardi et al. 2018), whom ironically, are also the most affected by food insecurity (Onyutha, 2018). The second sustainable development goal aims to end hunger, achieve food security and improved nutrition through promoting sustainable agriculture (UNDP, 2015). Thus, food security remains a key development issue and has remained a dominant topic in scientific and development discussions (Conceição et al., 2016).

## 1.4 Impact of population growth on food security in Africa

Africa's population is growing more rapidly than anywhere else in the world. The African population is projected to nearly double to 1.4 billion people in the next 35 years (Thomas & Zuberi, 2012; United Nations, 2013). Currently, food demand is already high and expected to further increase with population growth. Africa's food insecurity will likely worsen in rural SSA areas associated with poverty and high population densities, where farm sizes are small and are declining and where suitable land for agriculture has been exhausted and will likely be exhausted due to increased population pressures (Jayne et al., 2014). Population growth presents a critical global challenge, particularly for the agricultural sector through (i) its effect on land availability and quality (Willy et al., 2019), and (ii) on the ability of smallholder farmers to feed themselves and their families. Those that solely depend on rainfed agricultural systems for food and livelihoods are under further stress due to declining farm sizes.

Furthermore, increased population growth in rural areas of SSA could pose an obvious risk of continuous monocropping, over-cropping and/or overgrazing of already fragile agroecosystems, thus leading natural resource and environmental degradation (Burian et al., 2019). In cognisant of this, food production and availability will have to double just to meet the current food and nutritional requirements and more than double if hunger is to be reduced and avoid chronic and severe food shortages and food insecurity. Can agricultural production more than double in Africa by 2050? (Ittersum et al., 2016).

## 1.5 Impact of climate change impacts on food security in Africa

Smallholder agricultural systems in SSA are a major source of livelihood as they contribute towards food and nutrition requirements, income and employment (Tarawali et al. 2011; Thornton & Herrero, 2014). Smallholder agricultural production systems are predominantly rainfed, which is a great cause of concern as trends are showing an increase in water scarcity in SSA (Gizaw & Gan, 2017), with southern Africa countries, particularly Zambia and Zimbabwe showing a significant decrease in rainfall amounts. Contrastingly, South Africa and limited parts of East Africa and North Africa are experiencing an increase in rainfall (Girvetz et al., 2019). There are strong projections that SSA countries will be impacted severely by climate variability and change (Niang et al., 2014). Future climate change projections for SSA point to increased temperatures, with more frequent and intense occurrence of extreme weather patterns such as cyclones and heat waves (Serdeczny et al., 2017). Whilst projections of rainfall patterns remain uncertain, most CMIP5 models indicate that in much of eastern and central Africa annual rainfall will increase, while a decrease in rainfall is expected across many parts of western, southern and northern Africa. However, there is confidence that the rainfall pattern will change, particularly the onset, length and cessation of rainfall which may lead to significant changes to the growing season (Niang et al., 2014).

High exposure and high sensitivity of rural rainfed agricultural systems in SSA to climate, makes climate variability and change a key driver of food security through changes in temperature, shifts to the onset, length, cessation of the growing season, rainfall amount, pest and diseases occurrences and livestock health. Several scholars' project that climate variability and change may reduce smallholder farming systems productivity, particularly staple crop yields by 10 to 20 % in many SSA countries under optimistic scenarios (Roudier et al., 2011; Webber et al., 2014)). This is a significant decline in production for the already at-risk SSA population. The projections for the major grain crops namely wheat, sorghum, millet and maize are mostly negative across the African continent, with mean yield reduction of 17%, 15%, 10%, and 5% respectively (Ringler et al., 2010; Schlenker & Lobell, 2010). The anticipated negative impacts of climate variability and change are expected to further exacerbate the myriad challenges of rainfed agriculture-based livelihoods. Additionally, chronic food shortages are expected and food insecurity likely to worsen. As a result, smallholder farmers who practice rainfed agriculture are expected to become increasingly vulnerable and increasingly rely on natural resources, including destructing activities. Thus, these smallholder farmers end up putting intense pressures on agroecosystems, leading to serious land degradation, vegetation loss, deforestation leading to further global warming (Müller, 2013; Thornton & Herrero, 2014). Ensuring a future where food demand is met, and food security is achieved given the current and expected climate change impacts, agricultural extensification or intensification needs to be considered.

## 1.6 Option space to meet the increased food demand and food security

Rodriguez-Pose & Hardy (2015) argue that the challenge of food insecurity will be won or lost by improving the food production systems of the rural poor in SSA. There is wide agreement that addressing the global challenges posed by both population growth and climate variability and change on food security will require agricultural technologies and innovations that strengthen smallholder farmers' resilience and suit within the heterogenous biophysical and socioeconomic context of rural smallholder farming communities in SSA. SSA is regarded as land abundant (Chamberlin et al., 2014). Emphasis on achieving current and future food security is being placed on the expansion of crop land area or on increasing crop yields on existing cropland area (Erb et al., 2016; Springmann et al., 2018). Cropland area expansion has predominately contributed to crop production growth (Chamberlin et al., 2014; Levers et al., 2016). However, continued crop land area expansion, even in a few countries where unallocated land remains, is increasingly becoming problematic (Conceição et al., 2016; Deininger et al., 2017). Previous land use changes, particularly the conversion of grasslands and forests to land for agriculture contributed significantly to global warming (Jayne et al., 2019; Powlson et al., 2011; Smith, 2013). Moreover, in some areas, expansion of cropland area is no longer feasible (Chamberlin et al., 2014), or there is no more land available for further expansion (Deininger et al., 2017).

Alternative strategies to deal with rapidly increasing rural population densities, such as relocating from densely populated rural areas to less densely populated areas are being limited by various factors ranging from social, cultural and historically related factors. Furthermore, land reallocation and redistribution are resulting in tensions thus making relocation to less densely populated more difficult and problematic (Kalabamu, 2019). Issues of land constraints are becoming prominent throughout SSA due to increasing and competing demands for land for agriculture, urbanisation and nature conservation (Vliet et al., 2017). As a result, increasing food production through agricultural intensification is being advocated as an option for attaining food security in rural SSA. Intensification of current croplands by increasing cropping intensity and closing yield gaps (increasing farmer yields on existing cropping systems and farm land) may provide possible alternatives for increasing food production in smallholder agricultural systems in SSA (Wu et al., 2018). Moreover, there are wide or sizeable yield gaps in smallholder farming systems in SSA (Tittonell & Giller, 2013; Dzanku et al., 2015; Henderson et al., 2016) and currently smallholder farms have the largest potential of increasing food production on existing agricultural land (Mueller et al., 2012). Success in achieving agricultural intensification largely depends and places emphasis on improved and adapted agronomic practices (Gan et al., 2014), increasing resource use efficiencies (Fedoroff & Battisti, 2010), and the adoption rates of possibly new farming approaches (Makate et al., 2019).

## 1.7 Agricultural intensification in smallholder agriculture in SSA

There is consensus that the rising food demand urges for agricultural intensification (Godfray et al., 2012). There is also widespread agreement in the scientific and development arena that increased food production to achieve food security in rural must come with reduced environmental impacts in SSA and globally (Sala et al., 2017). This is in pursuit of achieving the second development goal (SDG-2)(Gil et al., 2019). However, achieving a model for agricultural intensification which would meet the increasing food demand, whilst ensuring environmental sustainability is challenged by poverty, inequality, climate variability and change and, land and natural resource degradation in the smallholder farming communities. The Green Revolution (conventional intensification of agriculture) brought great agricultural intensification in many developed countries and developing countries in Asia and South America, which largely bypassed SSA (Dawson et al., 2016a; Sheahan & Barrett, 2017). The conventional intensification of agriculture, which resulted in improved agricultural growth, productivity and food security in developed countries and many parts of Asia and South America, is now being regarded as incompatible with the current sustainable development goals (SDGs) (Schwoob et al., 2018). This conventional agricultural intensification model is based on its potential, as well as its externalities, with regard to suitability and has been castigated for not considering the real and complex relationships between farmland and nature, or between smallholder farmers and their farmland (Tscharntke et al., 2012). International agricultural research and development initiatives have not prioritised the importance of Africa's natural resources and agrobiodiversity in improving food production systems and ultimately food security. Rather, the focus has been on improving external input use especially inorganic fertilisers and agrochemicals. This has however raised a global concern on the sustainability of such initiatives (Mungai et al., 2016). Thus, intensification models which do not account for natural resource management and agrobiodiversity questions their suitability for improvement of current and future agricultural systems (Pingali, 2019). Hence, we are interested in models that aim to increase food production on existing agricultural land (intensify) and in parallel with explicit consideration for environmental sustainability. In the case of this study, we are particularly interested in the specific context of smallholder food production systems in rural SSA.

Two highly debated approaches to potentially intensify and ensure environmental sustainability have emerged in the scientific and development arena, that is sustainable intensification and ecological intensification (Godfray, 2015; Wezel, et al., 2015; Petersen & Snapp, 2015). Their multifaceted qualities have led to growing interests and strong support for their implementation in SSA (Pretty et al., 2011) While research keeps growing, in depth evaluation of the performance of these two models in terms of their direct and indirect consequences in diverse and heterogeneous biophysical and socioeconomic situations is needed for better understanding of their suitability and applicability in SSA smallholder farming systems for scaling. A variety of frameworks have been developed to assess and evaluate the impact of these models in smallholder agricultural systems. However, most studies have focused on the yield metric and do not evaluate multiple attributes of these models such as resilience, stability, adaptability and reliability (Smith et al., 2017).

Attention is now being paid to intensification models that utilise low-external input technologies or agroecologically based management practices (Altieri & Nicholls, 2013). Such technologies must hinge on harnessing farmers' knowledge and local resources to address productivity gaps in an environmentally sustainable manner (Srivastava et al., 2016). It is increasingly recognised that increasing agricultural production without the use of more land, water, fertilisers and pesticide is unlikely to be achievable unless ecosystem services provided by biodiversity in agroecosystems are placed at the heart of cropping systems than is currently the case (Holt et al., 2016; Landis, 2016). Therefore, is a surge in ecosystem services research. Agricultural ecosystems provide several provisioning, regulating and cultural ecosystem services and at the same time agriculture depends on a range of supporting and regulating ecosystem services such as pest suppression and nutrient recycling to enhance production (Balbi et al., 2015). Yet often, agricultural intensification discussions focus on the role of seeds, agrochemicals, and fertilizers without concomitant articulation of complementary role of biodiversity and ecosystem services.

Cropping practices that rely on agrobiodiversity and ecosystem services and functions are already being implemented by many smallholder farmers to improve their cropping systems, adapt and recover from climate variability and change impacts (Vignola et al., 2015). Harvey et al., (2017) argues that there are many agricultural practices that rely on agrobiodiversity and ecosystem services that could help smallholder farmers improve their food production systems while simultaneously increasing their resilience. Bommarco et al., (2018) highlight that there is large potential and opportunity of enhancing ecosystems services in smallholder agricultural through actual hands-on integration, proper exploitation and active management of ecosystem services in cropping systems. Whilst research and discussions on how to properly exploit ecosystems services to help smallholder farmers improve their food production systems is taking place in Central America and Asia , it is still largely missing in SSA (Vignola et al., 2015; Tran & Brown, 2018; Shah et al., 2019). Therefore, it remains unclear how these intensification models aim to incorporate and exploit ecosystem services for the benefit of cropping systems to improve food production and help attain food security.

Much of the research on agricultural intensification has focussed on assessing the productivity potential and economic aspects such as profitability, with less attention given to the model attribute and how they conform within the wider biophysical and socio-economic context of smallholder farmers in SSA (Snapp et al., 2018). Farmers may not implement approaches promoted by these models if they do not fit within the wider biophysical and socio-economic context. The applicability of these agricultural intensification models demands context-specific understanding and assessment of the biophysical and socioeconomic circumstances of smallholder farmers. Smallholder farming systems are heterogeneous in nature, with regard to farm sizes, production objectives, resource endowments, crop management strategies. Despite huge evidence of high productivity potential, previous conventional intensification models failed largely because they did not consider the highly heterogeneous biophysical and socioeconomic nature of smallholder agricultural systems (Chikowo et al., 2014). Therefore, examining farmers' perspectives on these intensification models and practices is essential to understand other concerns, besides agronomic and economic outcomes, that might guide smallholder farmers' decisions to accept, use and adopt these agricultural intensification strategies. Evidence on how these intensification models are applicable and fit within the wider and multiple biophysical and socio-economic circumstances across both spatial and temporal scale remains unclear. Therefore, there is a need to establish and figure out how ecological and sustainable intensification models fit within the heterogenous biophysical and socioeconomic context.

The agricultural sector is a major contributor of greenhouse gas (GHG) emissions (Adewale et al., 2019), and has significantly impacted global warming (Campbell et al., 2017; Tubiello et al., 2015). According to IPCC (2014) agriculture contributes between 25-30 % of global GHG emissions. There is a growing consensus that agricultural intensification in SSA should evolve in parallel with environmental sustainability to which GHG emissions from agriculture must be minimal or negligible (Minasny et al., 2017). Developing countries, especially countries in SSA face the challenge of attaining food security status and finding alternative, low carbon agricultural intensification pathways to help them concurrently meet their mitigation targets for mitigating global warming  (Wollenber et al., 2016). The recently agreed goal of mitigating global warming means that the fast growing GHG emissions from agriculture in SSA (Tongwane & Moeletsi, 2018), must be slowed down together with agricultural intensification. Reversing or slowing down agricultural driven GHG emissions from farming systems under going intensification will require intensification models that are efficient (Bajželj et al., 2014; Tilman & Clark, 2014). It remains unclear how these two (sustainable and ecological) intensification models may affect whole-farm GHGs balances, stabilise GHG emissions in cropping systems and contribute to mitigation in smallholder agricultural systems in SSA (Jin et al., 2017), which are experiencing serious climate change impacts. Therefore, developing approaches that enable assessments and whole-farm monitoring of productivity and GHG emissions in African smallholder agricultural systems would be vital in building scientific evidence that can inform policy on the design, applicability and implementation of these models to achieve sustainable agriculture, environmental sustainability and ultimately food security.

## 1.8 Why assess the value of ecological intensification in smallholder farming systems?

Current smallholder agricultural intensification paradigms are based models that have proved to be biophysically and socially incompatible with the heterogeneous smallholder farming communities in rural SSA. Scientific evidence and comparative research of sustainable and ecological intensification models is needed to assess (i) their value and unlock their potential to improve food production systems and environmental sustainability and (ii) assess their compatibility with diverse biophysical and socioeconomic context of smallholder agricultural systems and communities in SSA. Ecological intensification model of improving agricultural productivity has rarely been dealt with in heterogenous circumstances such as those of smallholder farming systems that characterise rural SSA, where climate variability and change will likely affect natural ecosystems, human livelihoods and economies (Tittonell & Giller, 2013). Ecological intensification aims at designing farming systems that make use of natural ecosystems services and functionalities, local resources and knowledge, decrease use of external inputs, improve resource use efficiency and facilitate the implementation of landscape approach which aims to overcome problems of sectorial approaches (Bommarco et al., 2013; Bommarco et al., 2018; Gaba et al., 2014). This model is deemed relevant and capable to guide in the redesigning African smallholder farming systems and, to deliver agricultural intensification that produces more output with less external inputs, while concurrently contributing to a healthy agroecosystem environment that provides multiple ecosystem services. Scientific evidence on ecological approaches to intensification in smallholder agriculture in SSA is not yet known or fully understood. This could be a new way to intensify smallholder agriculture and concurrently ensure environmental sustainability in SSA. The above global challenges, concerns and gaps highlighted to address the above challenges, and concerns present several avenues for investigation, part of which this thesis addresses.

## 1.9 Research question

How can ecological intensification be tailored to help rural African smallholder farmers to sufficiently improve food production systems and ensure environmental sustainability?

## 1.10 Aim

The thesis aims to assess the value of ecological intensification of smallholder agricultural systems to improve food production, livelihoods and environmental sustainability, in the face of climate change and variability. It seeks to highlight the suitability and applicability of ecological intensification in contributing to achieving food security, adapting and mitigating climate variability and change smallholder cropping systems.

## 1.11 Objectives

The thesis achieves its aim through the following objectives:

1. To assess the potential of ecological intensification in diverse smallholder farming systems in sub Saharan Africa.
2. To explore ways to incorporate and exploit ecosystem services to improve agricultural productivity through ecological intensification technologies in smallholder farming systems in South Africa.
3. To identify ways of enabling acceptance and use of ecological intensification technologies in the biophysical and socio-economic context of smallholder farmers in South Africa.
4. To explore and assess the productivity and environmental sustainability of current and redesigned cropping systems to deliver ecological intensification in smallholder farming systems.

To address the above objectives, a mixed methodology approach, supported by an extensive literature review, survey data, focus group discussions, theoretical models, biophysical crop model simulations and farm focussed greenhouse gas calculations were used and applied.

## 1.12 Study setting

South Africa as a nation is generally considered food secure. However, South Africa hosts high levels of inequalities and most households in rural areas are generally food insecure(De Cock et al., 2013; Tibesigwa & Visser, 2016). The focus of the study were two provinces, the Eastern Cape and Limpopo, which generally have the most food insecure households in South Africa. These two provinces are mainly rural and have the highest number of smallholder farmers highly dependent on rainfed agricultural systems for food production on less than 2 ha, growing mainly maize, legumes and vegetables (De Cock et al., 2013; Musemwa et al., 2015). Depending on their level of resource endowments, farmers own cattle, donkeys, goats, sheep, pigs and poultry. Limpopo province's population is estimated to be around 5.8 million (Statistics South Africa, 2015), consisting of approximately 1.6 million households, of which 0.4 million are engaged in subsistence agriculture (Statistics South Africa, 2016). Similarly, the Eastern Cape province is estimated to have a population of 7 million (Statistics South Africa, 2015) ,with approximately 1.8 million households, of which 0.5 million households are engaged in subsistence agriculture (Statistics South Africa, 2016).

In the Eastern Cape Province, the study was conducted in Raymond Mhlaba Municipality in Amathole District. This district is a semi-arid area. The mean monthly temperatures in the district range from 6.2°C to 20.8°C in July and 17.2°C to 36.0°C in February. The district has a bi modal type of rainfall. Thus, it receives both summer and winter rainfall, with average annual rainfall not exceeding 600 mm. The months of October to March receive the most rainfall with monthly averages ranging from 75 to 100 mm, while May to September experiences the least rainfall, averaging 25 to 75 mm monthly (Chari et al., 2018). Climate change in this area is difficult to project (Wintola, Otang & Afolayan, 2017). However, climate projections for Amathole District reveal that temperatures are projected to increase by between 1.5 to 2.5°C. Furthermore, an increased risk of heat waves during the late summer period is also expected. It is projected that a change in rainfall will occur but there is no consistency in the direction of expected change. (ICLEI- Local Governments for Sustainability, 2017). The challenges posed by the highly variable semi-arid climate, compounded by factors such as poverty inequality, low income levels among others compromise the adaptive capacity of local communities to adapt (Chari et al., 2018). In Limpopo province, the study was conducted in the Thulamela Municipality, Vhembe District, a semi-arid area situated in the north of the province. Rainfall in the area mostly occurs between October and January. In Ha Lambani, dry spells are common and frequent and often escalate into a severe drought (Ubisi et al., 2017). Climate projections for Vhembe district project that temperature is expected to increase by 1 to 3°C and rainfall will reduce by 5-10% by 2050 (Department of Environmental Affairs and Tourism (DEAT), 2004).

The areas described above are known as the former homelands. These areas are associated with both high human and livestock population densities. According to Statistics South Africa (2015), the population has grown significantly since 2011 in these two provinces, thus exerting more pressure on many land constrained households. The potential of household cropland expansion in these areas is limited due to historical, socio-political inequalities stemming from the former ‘Apartheid’ era, enacted through race-based land tenure rights. To buffer these land constrained smallholder farmers against a rapidly changing climate and severe food insecurity, South Africa needs to support relevant, feasible and sustainable agricultural intensification approaches that ensure long term productivity with minimal negative impact on the environment. How agricultural intensification approaches described earlier would apply in smallholder farmers context is still poorly documented in South Africa and other sub Saharan African countries. These two-study sites were selected because they typify smallholder farming systems and areas that can in similar forms be encountered in other villages, districts and provinces in South Africa and wider SSA.

## 1.13 Thesis outline

**Chapter 1** sets the scene for the PhD by providing a background and an introduction of the study. It presents the structure, the aim and objectives of the thesis.

**Chapter 2** sets the stage with ecological intensification as a suitable model to intensify food production systems and achieve environmental sustainability in smallholder farming areas of SSA. This results from an extensive review of conventional and sustainable intensification models on their suitability, sustainability and challenges experienced in smallholder farming systems in SSA. This chapter addresses objective 1.

**Chapter 3** deals with agronomic challenges linked to heterogeneous smallholder farming systems and how to exploit and incorporate ecosystem services to address these challenges. The chapter highlight the importance of recognising and responding to heterogeneity in smallholder farming systems in rural areas of South Africa. Few critical challenges were identified and can be successfully addressed by ecological intensification technologies through exploiting specific ecosystem services to improve food production systems in heterogeneous biophysical and socioeconomic context of smallholder farming in South Africa. This chapter therefore addresses objective 2.

**Chapter 4** identifies and assess the applicability of ecological intensification technologies in the heterogeneous biophysical and socioeconomic smallholder context. The chapter employs a theoretical modelling framework to present the synergies and socioeconomic trade-offs of ecological intensification technologies associated with different farm types and farmers. Recognising this inherent heterogeneous nature of farming communities, it highlights the importance of assessing technologies holistically to enable acceptance and use (adoption) of adapted strategies in smallholder farming communities. This chapter addresses objective 3.

**Chapter 5** offers a concurrent assessment of the productivity and environmental sustainability of smallholder farming systems. It assesses productivity (yield) and environmental sustainability (GHG emission intensity) of maize-based cropping systems in different farm types in rural South Africa. It relies on a modelling approach encompassing a crop model and a farm focused greenhouse gas calculator to assess the productivity, land use efficiency and mitigation potential of conservation agriculture (CA) practices. Lessons are presented and discussed through their potential to guide the remodelling or redesigning of smallholder farming systems to better address the competing ambitions of increased production and ecological sustainability and deliver ecological intensification. This chapter addresses objective 4.

**Chapter 6** reflects on previous chapters and summarises the main findings of Chapter 2, 3, 4 and 5. It then synthesises the research findings and constructs emerging conclusions pertaining to ecological intensification of smallholder farming systems in SSA. Finally, it proposes future work to further consolidate and advance knowledge in this study area.

# CHAPTER 2

# A review on the potential of ecological intensification to improve food production systems in smallholder agriculture in sub Saharan Africa

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## Abstract

Population growth is occurring more rapidly in sub Saharan Africa (SSA) than elsewhere in the world. Food demand is therefore expected to increase, resulting in more chronic food shortages and food insecurity. With 70% of Africans dependent on rain-fed agriculture as a source of food production, climate and climate variability changes are adversely affecting countries in SSA. Agricultural yields are well below attainable levels in smallholder farming systems in Africa and this particularly affects the ability of these farmers to raise enough food for household subsistence. Globally, the focus is on increasing agricultural productivity through agricultural intensification to achieve food security and alleviate poverty in Africa. This paper explores ecological intensification, which offers synergistic opportunities for increasing agricultural productivity and ensuring environmental sustainability in resource constrained and climate stressed environments. We highlight its fit, potential benefits and strengths in smallholder agricultural systems and steps to be taken to support its implementation and development in SSA. We recommend the need for further studies aimed at strengthening both the scientific base and expected benefits of ecological intensification options in SSA smallholder agricultural systems to improve promotion and adoption.

**Key words**: food production; smallholder agriculture; ecological intensification; environmental sustainability

## 2.1 Introduction

The agricultural sector will face a serious demand for more food as the world population is expected to increase by 3 billion people in the next three decades (Godfray et al., 2012). Water and food security are already and will continue to be, major global challenges, particularly in semi-arid areas of SSA (Misra, 2014). SSA already has the highest proportion of food-insecure people in the world (FAO, 2012), which, in combination with the growing population, will further stress food security in the near future (Sasson, 2012; UN, 2015). This urges for increased agricultural production in smallholder farming due to its importance in rural development, particularly in SSA. Increasing productivity in these areas will help tackle food security and poverty reduction (Lipper et al., 2014).

It is estimated that about 70 % of Africans in SSA are dependent on rain-fed agriculture for their livelihoods, on small areas of land, often less than 2 ha (Vignola et al., 2015). Despite large areas of unexploited arable lands in SSA, the potential for increasing food production through cropland expansion is limited by competition from forestry, nature reserves, urbanisation and other land resource uses (Chamberlin et al., 2014; Vliet et al., 2017). These smallholder farmers live in marginal areas and are typically financially constrained to maintain or to increase productivity in these fragile remote locations. In addition, they generally lack access to technical assistance, markets, credit, or government support and are vulnerable to a variety of stresses, including a steadily degrading natural resource base (Vermeulen et al., 2012; Cotula et al., 2012;Vorley et al., 2012)

Climate change, including climate variability changes in SSA, is expected to negatively impact and further stress African agriculture and livelihoods (Connolly-Boutin & Smitt 2016). Given the projected increased variability in rainfall and rising temperatures (Serdeczny et al., 2017), and the low coping or adaptive capacity of smallholder farmers, considerable adverse impacts are expected on rain-fed dependent food production systems (Zinyengere et al., 2014). These phenomena, ultimately affect the ability of smallholder farmers to raise enough food to feed themselves (Descheemaeker et al., 2016). The lack of sustainable alternative livelihood options results in relief being sought through activities that lead to the destruction of natural resources, intensifying further pressures on agroecosystems where they live (Müller, 2013; Thornton & Herrero, 2014). Pretty et al. (2011) emphasise that SSA countries must find novel ways to boost agricultural productivity if they are to become self-sufficient and not rely on food aid. How to achieve current and future food security globally and especially in SSA is thus a major question in the development and scientific communities (Pretty et al., 2011; Godfray et al., 2012).

Conventional intensification has been the main strategy for increased agricultural production for decades (Garibaldi et al., 2016), but its effects on poverty alleviation were limited, especially for smallholder farmers in SSA. (Pretty et al., 2011; Patel, 2013). It provided a platform for economic growth in many developed countries but it did not have the same success in developing countries in SSA (Pingali, 2012). Improvements were limited due to biophysical constraints, such as the depletion of soil fertility and technological interventions, which did not account for the socially diverse and spatially heterogeneous farms and farming systems in SSA (Sanchez, 2015; Dawson et al., 2016). For instance, Chikowo et al., (2014) attributed the failure to the promotion of conventional intensification technologies which did not take into account the different socio-economic circumstances, resource constraints, farmer objectives and farm types in SSA. Similarly, Dawson et al., (2016) highlighted that the use of improved seeds, agrochemicals and irrigation had overall limited success, due to locally unsuitable recommendations in terms of seed varieties, input cost or lack of human and institutional capacity. Furthermore, conventional intensification came with detrimental impacts on the environment and increased greenhouse gas emissions (Phalan et al,, 2014). Agriculture hence needs to find novel ways to reduce long-term reliance on environmentally damaging agrochemicals and fertilizers, while still ensuring its future competitiveness (Ehrlich & Harte, 2015).

Driven by the need for increased agricultural production and environmental sustainability to achieve sustainable food security, new forms of sustainably oriented agricultural intensification must emerge in response to the United Nations Sustainable Development Goals (SDGs) on zero hunger and biodiversity conservation. Therefore, in pursuit of the SDGs, agricultural intensification which would address both the immediate need for increased production and long-term sustainability would be the most appropriate (Kuyper & Struik, 2014; van Noordwijk & Brussaard, 2014). In addition, the large diversity of farms and farming systems in SSA calls for agricultural intensification options that fit and are adapted to the context in which smallholder farmers operate.

Two agricultural intensification models, namely, sustainable intensification and ecological intensification, have gained momentum in the scientific and development world. These two models of intensification are closely linked in terms of definitions, principles and practices thus creating confusion in their meaning, interpretation and implications (Wezel et al., 2015). However, it is often argued that ecological intensification is more clearly defined, with a better theoretical basis (Petersen & Snapp, 2015; Wezel et al., 2015). The major difference is the role played by nature in the actual design of the farming systems (Tittonell, 2014) and in the possible synergies amongst food security, global change adaptation and mitigation. This paper explores the ecological intensification paradigm, how the model particularly fits smallholder farmers, its potential benefits and strengths in typically resource constrained and climate stressed environments such as those of smallholder farmers and steps that must be taken for a particularly promising ecological intensification paradigm to guide SSA remodelling of smallholder farming systems towards sustainable increased food production.

## 2.2 Ecological intensification and smallholder agriculture in SSA

Ecological intensification is defined as a means of generating more output from the same area of land while reducing the negative environmental impacts by decreasing the reliance on anthropogenic inputs through the management of regulating and supporting ecosystem services in agricultural practices (Bommarco et al., 2013; Tittonell, 2014). The concept of ecological intensification seeks to ensure long-term productivity through intensifying ecological processes that supports agricultural production such as biological pest regulation, nutrient recycling and pollination. It aims to achieve this through the restoration of biodiversity, ecosystem services and functions, and through promoting beneficial biological interactions, processes and organisms (Bommarco et al., 2013; Gaba et al., 2014; Tittonell, 2014). It should be noted that ecological intensification does not aim to entirely replace external inputs such as inorganic fertiliser but rather aims to reduce over reliance on external inputs by promoting beneficial interactions through judicious use of external inputs. It aims to complement or (partially) replaces external inputs such as agrochemicals and fertilisers with production-supporting ecological processes, interactions and organisms such that production is maximised while environmental impacts are minimised. Approaches of ecological intensification may include, non-exhaustively, the practice of agroecology (Altieri et al., 2012), organic agriculture (Jensen et al., 2015), diversified farming systems (Gurr et al., 2016), nature mimicry (Tittonell, 2014), and some forms of conservation agriculture (CA) (Giller et al., 2015) and of agroforestry (Wezel et al., 2015).

In SSA, smallholder farmers operate under harsh environmental conditions with limited resources. As a result, the productivity of smallholder agricultural systems is low, and the yield gaps are large. Ecological intensification seems a promising agricultural intensification option for African smallholder farmers and is receiving widespread attention and interest from African governments and development agents. This is because of its ability to improve crop yields with limited external inputs and resources and its ability to protect the environment from further degradation (Tittonell, 2014). Therefore, the challenge of ecological intensification in smallholder agricultural systems in SSA is to concurrently increase crop yields and stability over time, increase the resilience of farming systems to climate variability and change impacts and reduce land and environmental degradation.

### 2.2.1 Why ecological intensification is fit for smallholder farmers in SSA?

Smallholder farming systems in SSA are highly dependent on local resources, varieties, breeds, and family labour to produce food due to external input and financial resource constraints and limitations (Sheahan & Barrett, 2017). Therefore, most of the farming systems have remained ecological, maintained and enhanced by supportive and regulatory ecological processes (Tittonell & Giller, 2013), steered through location-specific indigenous knowledge, which still constitute the backbone of smallholder agriculture in many places in SSA (Tittonell & Giller, 2013; Mapfumo et al., 2016). The notion that smallholder farmers can master the supportive and regulatory ecological mechanisms, means that moving from current practices to ecological intensification thus requires less efforts for these low-input systems compared to high-inputs systems. This smaller gap makes ecological intensification a better fit and a promising paradigm for remodelling smallholder farming systems both in response to existing capacities, as well as the immediate need for long term sustainable production increases and environmental sustainability in SSA.

Due to the low input nature of smallholder agriculture, pests, diseases and weeds and, low inherent soil fertility and soil degradation through nutrient and organic matter depletion have remained major constraints to food production and contribute to chronic poverty and food insecurity in SSA (Nezomba et al., 2014; Vanlauwe et al., 2014; Tully et al., 2015; Onyutha, 2018b). While increased use of external inputs especially inorganic fertiliser is unavoidable if major productivity increases are to be achieved in SSA. Strategies to address food security will require local innovation to increase food production sustainably and affordably for smallholder farmers and farming systems in SSA. These local innovations must reduce the environmental impact of agriculture and must aim to reduce the dependence of agriculture on non-renewable resources such as external inputs in the long run. Ecological intensification has been proposed as a clearly defined alternative that aims to complement and (partially) replaces the limited non-renewable external inputs such as agrochemicals and inorganic fertilisers with production-supporting ecological processes, interactions and organisms in the long run. The ability of ecological intensification to take different forms and factor in local innovation makes it highly fit for smallholder farmers as they are not only an integral part of the innovation system but a valuable source of the innovation process.

Many of these production-supporting ecological processes used to foster ecological intensification are rich in biodiversity, resilient, water and nutrient efficient, which have shown stability amid climate and economic challenges in SSA (Khan et al., 2010; Vanlauwe et al., 2010; Altieri et al., 2012). Smallholder farmers are highly vulnerable to climate change due to their dependence on rain-fed agriculture. Therefore, these production-supporting ecological processes used to foster ecological intensification can increase the resilience of smallholder farming systems. In addition, smallholder farmers in SSA are resource constrained in terms of external inputs such as fertiliser. Therefore, incorporating these production-supporting ecological processes that help increase the efficiency of the limited external input resources make ecological intensification a better fit in a climate stressed and resource constrained environment such as that of many smallholder farmers in SSA.

### 2.2.2 The potential of ecological intensification to transform smallholder agriculture in SSA

Transformation of smallholder agricultural systems to achieve food security will require agricultural intensification options that have potential to improve the resource use efficiency of the limited external inputs, soil fertility, pest, and weed suppression, reduce risk of crop failure, improve overall crop productivity and environmental sustainability. Ecological intensification options or approaches have the potential to address the above-mentioned constraints to increased crop production and yields and achieve some of the goals such as environmental sustainability, particularly in resource constrained African smallholder farming systems and communities. Ecological intensification through options such as crop rotations, intercrops, cover crops, and green manures offer sustainable long-term benefits in response to the above-mentioned constraints and challenges. Even though these ecological intensification approaches or options are still not completely understood (Heijden et al., 2015; Lehmann &

Kleber, 2015; Adhikari et al., 2018), evidence on their potential in smallholder farming systems in SSA is still building up.

Ecological intensification options or approaches are particularly relevant to land and resource constrained African smallholder farmers and have the potential to improve resource use efficiency in their farming systems. For example, Kermah et al. (2017) showed that maize-grain legume intercropping increased land productivity and productive use of environmental resources, thus enhanced resource use efficiency. Adhikari et al. (2018) reported that in Sierra Leone, krain krain a leafy vegetable, when grown under ecological approaches yielded higher and saved farmers' financial resources than when grown conventionally. Moreover, by harvesting seeds from their second crop, farmers no longer need to buy seeds. Purchasing seeds is necessary when krain krain is grown conventionally because such plants are harvested by removing them from the garden before there is any seed-set.

One of the major constraints to higher crop productivity among smallholder farmers in SSA is poor soil fertility related mainly to continuous monocropping without replenishment of depleted nutrients (Berge et al., 2019). Several scholars, Vanlauwe et al., (2011), (2014), Holden (2018) and Jayne et al., (2019) advocate that for agricultural intensification to be successful in SSA a much higher intensity of external input use of inorganic fertilizer per hectare will be needed to improve soil fertility. The scholars also argue that although legumes add nitrogen, they do not add other nutrients to the soil therefore, inorganic fertilisers are necessary to kick start the process of nutrient recycling. They argue that nutrient recycling is good, but there must be something to recycle. Therefore, inorganic fertilisers are necessary to catalyse nutrient recycling for sustainable agricultural production in most nutrient deficient soils of smallholder farms in most areas of SSA. While this is might be the case towards increased food production in most smallholder agroecosystems, Sommer et al., (2014) point out that it is not only about intensifying inorganic fertilizers use in smallholder agricultural systems, but also about what other agroecological ecosystem services and functions can be harnessed, what agroecological principles and practices can be done and accessed by smallholder farmers to improve soil fertility and productivity in their climate stressed and resource constrained environments. Their argument is based on a study by Rusinamhodzi et al., (2012), that showed the potential of ecological intensification in smallholder agricultural systems. In this study, the radical success of CA (no tillage, mulching and intercropping/rotation with a legume) in an on-farm experiment in Mozambique is highlighted.

CA not only improved the response of maize to fertilizer, but also the control treatment without fertilizers but with the three agroecological principles of CA. In this case, the control treatment yielded significantly more than the (no-till) treatment that received the maximum nitrogen (N) and phosphorus (P) application rates. Other CA studies and experiments have reported similar results (Thierfelder and Wall, 2010; Thierfelder et al., 2012; Mupangwa et al. 2012; Jat et al., 2014 Thierfelder et al., 2015). These studies confirm that in addition to increased use of inorganic fertilisers, soil fertility and productivity can also be improved through harnessing and exploiting ecosystem services, functions and agroecological principles. Therefore, highlighting the potential of ecological intensification contribute to soil fertility improvement in smallholder agricultural systems in SSA.

A review by Franke et al., (2018) highlighted that smallholder farmers grow grain legumes that have a net field N balance of zero hence they do not add a lot of N to the soil. Mapfumo, (2011) also asserted that current N inputs from Biological Nitrogen Fixation (BNF) on smallholder farms remain as low as 5 kg N ha$^{-1}$ year$^{-1}$ due to factors that include poor choices of legume types/varieties, small areas allocated for legume production, and poor soil fertility (particularly P deficiency) and rainfall variability that lead to poor biomass accumulation. Nevertheless, Kermah et al., (2018) in a maize-legume rotation or relay study showed the potential of ecological intensification options to improve soil fertility and productivity in soils of low fertility status. In this study, it was concluded that low soil fertility stimulates grain legumes to rely more on atmospheric $N_2$-fixation than on soil N for growth resulting in larger partial soil N balances of grain legumes grown in the low fertility fields.

Moreover, ecological intensification through proper selection of suitable legume types/varieties and judicious application of inorganic fertilisers to complement the BNF has potential to provide a win-win situation in such a case where limited quantities of external inputs such as fertiliser are used, more N may be available for the subsequent crop than after a cereal. This is further asserted by Mapfumo, (2011), that there is potential for legumes to contribute to soil fertility improvement through BNF, as legumes have capacity to generate 200–300 kg N ha$^{-1}$ under farmer management conditions, reducing N fertilizer inputs for subsequent maize by 50–100 kg ha$^{-1}$ in a single cropping season. Legumes derive 50–90% of their N requirements from N-fixation, nearly eliminating the need for external N fertilization. Furthermore, Vanlauwe et al., (2019) highlighted that legumes provide organic inputs with positive impacts on soil chemical, physical and biological properties, thus have the potential of improving both soil fertility and crop yields in smallholder cropping systems. Masvaya et al. (2017) demonstrated intercropping to be a robust ecological intensification option for resource-poor smallholder farmers. They showed that by intercropping maize and cowpeas, soil fertility and crop yields improved across all seasons and soils. Furthermore, Wittwer et al. (2017) highlighted that adding nitrogen-fixing legume species as a cover crop can improve nitrogen nutrition of the succeeding main crop and increase the soil nitrogen organic pool. Rusinamhodzi (2015) also showed that legume-cereal rotations facilitate soil fertility replenishment while, at the same time, minimising pest and disease build-up. Thus, when grain legumes are incorporated in cropping systems, they have the potential to improve soil fertility in nutrient limited soils and reduce the burden of over reliance on large quantities of anthropogenic inputs beyond the reach of many smallholder farmers.

In addition, ecological intensification options or approaches are particularly important for crop protection in smallholder cropping systems where most farmers cannot afford expensive agrochemicals for crop protection. These options have shown potential wide-spread benefits of natural pest control at the field scale. Diversification of crops in space and time is one ecological intensification approach to minimise pest pressure and build-up in crop fields (Barzman et al., 2015). For example, the ‘push-pull’ technology, where selected plants as inter-crops either repel the insects or control or suppress certain species resulting in improved crop yields (Hassanali et al., 2008; Khan, James, et al., 2008; Midega et al., 2011, 2014). Midega et al. (2015) demonstrated ecological management of cereal stem borers in African smallholder agriculture through this ‘push-pull’ technology by planting Napier grass as a border crop around plots of maize and resulted in highly significant reductions in stemborer infestation in maize, with concomitant yield increases of 1–1.5 t ha$^{-1}$. Studies by Maluleke et al., (2005), Chabi- Olaye et al., (2005) and Chabi-olaye et al., (2005) further showed the importance of ecological intensification for crop protection. In these studies, they highlighted that intercropping cereals with non-host legumes or other non-host crops does help to reduce yield losses and attacks from stemborers in different parts of SSA. Furthermore, Mhlanga et al. (2015) observed that the inclusion of cover crops in rotations of maize based conservation agriculture systems reduced weed numbers and dominance of problematic weeds over time. This potentially can lead to a less intense weeding schedule, which is cost effective and affordable for smallholder farmers practising CA (Thierfelder et al. 2013; Thierfelder et al. 2015).

Climate change is expected to impact negatively on most rainfed agricultural systems and further increase the vulnerability of smallholder farmers in most areas in SSA. However, ecological intensification through diversification of crops in space and time has the potential to increase resilience, reduce vulnerability by ensuring harvest security and ultimately improve food security in these climate stressed and vulnerable production systems. Rusinamhodzi et al. (2012) showed that maize-legume intercropping as an option for ecological intensification has the potential to reduce the risk of crop failure and improve productivity, income and food security in vulnerable production systems. Kermah et al., (2018) showed that in regions with erratic rainfall patterns such as the Guinea savannah of West Africa, ecological intensification has the potential to mitigate risk of crop failure. In this example, the relaying of cowpea into maize as an option for ecological intensification option improved crop yields and helped mitigate the risk of total crop failure. These results concur with those of  Rapholo et al., (2019) that also showed that relaying legumes into maize has potential to reduce the risk of crop failure in a high climate risk environment. In this example, lablab, a locally underutilised legume was relayed into maize in a high climate risk environment of Limpopo, South Africa and the maize yielded significantly higher than sole maize. Recently, Wittwer et al. (2017) concluded that cover cropping as an option for ecological intensification has the potential to reduce the risk of crop failure through protection against soil erosion and reduction of nutrient losses.

Climate smart agriculture (CSA) is an approach that rose from considering adaptation and mitigation challenges faced by smallholder farmers in SSA (Lipper et al., 2014). It aims to achieve farming systems that utilise ecosystem services to support productivity, adaptation and mitigation (Harvey et al., 2014). Despite differing in concepts, ecological intensification options and climate smart agricultural strategies translate into highly comparable implementations. For example, crop diversification, an option in both CSA and ecological intensification, provides an adaptation approach by improving resilience to climate variability in the short term and climate change in the long term, consequently reducing the risk of total crop failure and improving food security. It also offers opportunities to enhance environmental sustainability through mitigation properties, noticeably through the reduction of pesticides and fertilizer use, or through increased agroforestry and consequent increased carbon sequestration.

### 2.2.3 What can be done to make ecological intensification happen in SSA?

The transition towards ecological intensification to guide SSA remodelling of smallholder farming systems should be viewed as a knowledge intensive process, aimed at improving the resource use efficiency of limited external input resources to enhance productivity in resource constrained smallholder farming systems of SSA. It should not be perceived as the promotion of old indigenous traditional practices or promotion practises that do not require the application of external inputs such as inorganic fertiliser. The science supporting ecological intensification is relatively young and is still being gathered. Smallholder farming communities and agricultural landscapes are heterogeneous. Promotion of blanket recommendations across heterogenous farming communities and agricultural landscapes will not achieve the intended outcomes of improved productivity and environmental sustainability. Therefore, agricultural research scientists, extension officers, the government and private sectors must engage with smallholder farming communities to co-learn and co-explore specific agroecological and socio-economic conditions to be addressed. It is therefore important to identify and address what we poorly know. A successful transition will require an in-depth understanding of the farming environment (i.e. weather/climate patterns), the current range of crops, soil types, soil fertility strategies, pest suppression strategies, water conservation, other local practices, markets and infrastructure. More specifically, an understanding agroecological mechanisms at work in smallholder agroecosystems is needed, using agrobiodiversity as leverage for intensification and exploring the multiple and complex links between the technical dimension of practices and socio-economic and trade-offs at both household and community level.

A successful implementation will require all interested stakeholders to engage

(i) for an in-depth assessment or evaluation of current farming practices on their production, economic and environmental performance to better organise the transition of remodelling towards ecological intensification of smallholder farming systems.

(ii) to delineate the production, environmental and economic objectives of the alternative production systems which will then drive the design of the alternative production systems.

(iii) To identify or generate alternative production systems that may potentially represent the transition of remodelling current farming systems or farms towards ecological intensification. The ideas and suggestions of these alternative innovative may take several forms and directions, for instance, the introduction of a combination of crop varieties and crop types that harness complementary environmental services and interact to help control pests and diseases, new cropping patterns in space and time to help improve land use efficiency and provide additional income for the farmers The ideas or suggestions can emerge from the assessment from step (i), as well as from previous innovative studies in other production areas or similar production systems through literature search.

(iv) to identify the key resource persons likely to contribute to the conceptualization of the selected alternative production system, its deployment as scenarios to be simulated, and their detailed qualitative and quantitative characterization.

(v) to identify real farms, farm cases, or experimental sites where these alternative production systems are to be tested and evaluated.

(vi) to define, design and characterize scenarios linked to both the alternative production system and the farm case selected. Each scenario must (a) respect the production, environmental and economic objectives defined in step (ii), (b) take into account the context that can prevent or encourage the development of specific activities or practices, (c) start from the initial configuration and management of the farm, and (d) take in account needs of the crops and animals that it includes.

(vii) to assess both quantitively and qualitative each scenario. Flexibility should be factored in to help adapt to different situations encountered in the design process. Flexibility makes it possible to imagine a variety of redesigned alternative production systems, allowing the integration of different combinations of productive activities according to various combinations of resources. The different steps and tools on which this process will be based should not be specified to a crop, a context or a farm.

(viii) to discuss the benefits, trade-offs and applicability of the scenario simulated with regard to the initial objectives based on the outputs of the simulations. These discussions must involve all the actors and stakeholders who participated in the scenario's design process and description. Both the results of the quantitative and qualitative assessments are to be used in the discussions.

## 2.3 Conclusion

The African population is rapidly growing and must increase its agricultural production sustainably, particularly in the smallholder, sector to meet its growing demand for food. This research advocates ecological intensification as a clearly defined alternative agricultural intensification paradigm that` is affordable and applicable to African smallholder farming systems. We highlighted that it is aimed at addressing both crop yield increases, and sustainability traits required to achieve UN Sustainable Development Goals on zero hunger and biodiversity conservation. We particularly emphasised the fit of ecological intensification for resource constrained smallholder farmers. We later discussed its potential in terms of sustainable yield improvement, among smallholder farming communities in Africa and its capacity to make smallholder farming systems resilient, productive and environmentally sustainable. We recommend that transition towards ecological intensification remodelling of smallholder agricultural systems incorporate smallholder farmers views, circumstances and realities of their agroecosystems. The transition towards ecological intensification comes with significant demand for further understanding and evidence to confirm its value in improving smallholder production and long-term sustainability in the face of climate challenges and African development ambitions.

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# CHAPTER 3

# Developing pathways to improve smallholder agricultural productivity through ecological intensification technologies in semi-arid Limpopo, South Africa

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## Abstract

Agriculture faces an enormous global challenge of feeding 9 billion people by 2050. This means a comprehensive intensification of agriculture is required. Ecological intensification is gaining momentum as a clearly defined vision for increasing agriculture productivity and sustainability. How ecological intensification could be tailored to benefit smallholder farming systems in sub Saharan Africa (SSA) remains the major question. In this study, we develop pathways relying on ecological intensification technologies and suiting different farm types of smallholder agriculture based. This study relies on multiyear engagements with agricultural experts and smallholder farmers in Ha Lambani, South Africa and leads to the identification of farmer groupings. We analyse 40 in-depth semi-structured interviews with farmers which leads to the identification of farming patterns and constraints. We present how farming systems analysis of challenges and constraints following the DEED (Design, Explain, Evaluate and Design) cycle approach helps to identify and link specific ecosystem services with suitable ecological intensification options. We conclude that the expert-based classification of farmers offered a more contextualised representation of farming system heterogeneity, where tailored ecological intensification technologies could play a major role in improving agricultural productivity. Beyond this community, it emphasises the need to consider farmers' type heterogeneity as a strong decision parameter for targeting ecological intensification.

Key Words: farm types; smallholder agriculture; ecological intensification; ecosystem services

## 3.1 Introduction

In southern Africa, smallholder farming is dominated by dryland crop production. The regional average maize grain yields ranged from 0.3 to 2.2 t/ha during the period 2008–2012 (FAO, 2014). South Africa is generally considered a food secure nation (De Cock et al., 2013), but many households in rural areas are food insecure (Pereira et al. 2014). About 35.2 % of the South African population live in rural areas (Statistics South Africa, 2015) and practice subsistence agriculture (Thamaga-Chitja & Morojele, 2014). They rely on agricultural activities for their livelihoods and are amongst the poorest and most vulnerable in the country (Tibesigwa et al. 2014; Ncube et al. 2016). The rural farming households are particularly vulnerable to climate and other disaster risks because they are mostly dependent on rain-fed traditional agriculture (Mwenge Kahinda & Taigbenu 2011; Kong et al. 2014) and have a low adaptive capacity due to technical, financial and infrastructural constraints (Gbetibouo et al. 2010).

In South Africa and most surrounding countries in Southern Africa, agriculture and agricultural related activities contribute to most of the employment in rural areas (Dercon & Gollin, 2014). Smallholder agriculture has the potential to generate more employment opportunities and income and consequently, improve livelihoods in rural areas of South Africa (Shisanya and Hendriks 2011; Mpandeli & Maponya 2014). Therefore, improving agriculture is considered a viable and sustainable alternative in reducing rural poverty in South Africa and other sub Saharan African (SSA) countries (Adekunle 2014; Thamaga-Chitja & Morojele 2014; Shisanya & Mafongoya 2016). With proactive technical and policy support, smallholder farmers can realise their potential to become competitive in their agricultural production activities. Thus, the improvement of smallholder farming is a high priority in South Africa's development of rural communities (Aliber & Hall 2012; Kepe & Tessaro 2014).

The manner in which agricultural technologies and innovations should be promoted in SSA to improve production and sustainable livelihoods through smallholder farming is largely debated (Wainaina et al. 2016). Technologies on sustainable land use and improved agricultural productivity such as conservation agriculture (CA) and in situ rain water harvesting have been developed, promoted and scaled out in the past 30 years in SSA (Bidogeza et al. 2009). However, these technologies have been only partially adopted (Giller et al. 2015), and most have not been fully adopted (Wainaina et al. 2016). This is because most interventions are not reflective of smallholder farmer circumstances and fail to acknowledge the realities of smallholder farmers, be they environmental, social or their environmental perceptions or the strategies used to meet their food security needs (Nhantumbo et al., 2016). For example, Giller et al., (2009) question the suitability and effectiveness of conservation agriculture (CA), despite its heavy promotion in SSA, especially in smallholder agriculture, highlighting a possible mismatch between the conditions required for all CA principles to be adopted by farmers and the circumstances that characterise and constrain smallholder African farming systems. This disconnect undermines effective engagement between farmers, extension services and researchers for the effective improvement of technologies and their adoption. Therefore new pathways of fostering agricultural interventions in South Africa and SSA are needed before scaling up such interventions (Whitbread et al., 2010; Sanyang et al., 2016). Agricultural technologies and interventions aiming to enhance production, income, and household livelihoods, must capture the contrasting financial, technical and biophysical circumstances within and across the heterogeneous agro-ecologies in smallholder agriculture in SSA (Baudron et al., 2015; Giller et al., 2015). This must include the differing socio-economic circumstances within the sector.

Effectively identifying and integrating major issues that guide smallholder farmers' decision making is, therefore, important to unlock current low adoption rates of practices such as conservation agriculture or in situ rain water harvesting among others (Nhantumbo et al., 2016). A practical way to understand smallholder farmers' decision-making is to identify their systems' performance, efficiency levels, challenges and opportunities. Understanding the sensitivity and exposure of the farming systems to climatic, social, economic or biophysical shocks could also help. Different modelling frameworks can be used to achieve the above. However, a successful farming system analysis model requires an understanding of farm systems heterogeneity. Amongst farm households with similar production goals, biophysical and resource endowments, farm typologies effectively classify the heterogeneity of farmers' motivations and socio-economic circumstances in relation to their farming systems (Bidogeza et al., 2009; Chikowo et al., 2014; Chenoune et al., 2016). Two approaches could be used to identify farm types in smallholder agriculture in SSA. The first is a bottom-up participatory approach where every farmer is consulted and engaged through field visits, discussions and interviews. The second is a top-down approach where key informants are interviewed to identify heterogeneity traits and generate typologies as shown by Tittonell et al., (2005) and Zingore et al., (2007). Whilst the first approach cannot be implemented on a large scale (lack of human and time resources), it allows for a better description of farmer's anticipation, capacity and willingness to adopt new management strategies and agro-technologies. The second approach has the potential for large scale implementation in cases where time and other resources are limiting. The classification criteria depend on the goal of the typology and the kind of data available. Furthermore, agricultural scientists are being encouraged to develop farm typologies to support a more tailored approach to agricultural development and innovation (Kuivanen et al., 2016).

In SSA, two models of fostering agricultural development and innovation to improve smallholder agriculture have gained momentum, namely sustainable and ecological intensification (Petersen & Snapp, 2015). The two are closely linked in terms of definitions, principles and practices, thus creating some confusion in their meaning, interpretation and implications. However, it is often argued that ecological intensification is more clearly defined, with a better theoretical basis (Petersen & Snapp 2015; Wezel et al. 2015) The major difference between these two models is that for ecological intensification, agricultural systems are designed to benefit from ecological processes and functions, including biological control of biotic stressors and efficient use of available resources and ecological services (Bommarco et al., 2013; Tittonell 2014; Kovács-Hostyánszki et al., 2017). Sustainable intensification which is defined as increasing yield per unit input (Garnett & Godfray), on the other hand, does not have a focus on ecological processes, although these can be incorporated if they contribute to reduced inputs, increased outputs or enhanced efficiency. In recent literature, sustainable intensification has tended to have more of a focus on technological innovation and increased production without environmental impacts (Loos et al., 2014; Kuyper & Struik, 2014; Godfray 2015).

In this study, we focus on and explore ecological intensification using the top-down approach. Ecological intensification is defined as a means of increasing agricultural production and environmental services while reducing the need for external inputs and capitalising on ecological processes that support and regulate primary productivity in agro ecosystems (Tittonell 2014). Ecological intensification seeks to ensure long term productivity and sustainability through the restoration of biodiversity and a full array of ecosystem functions and services that support food production and human well-being. It aims to achieve a healthy environment that provides multiple ecosystem services (i.e., clean water, improved soil fertility, pest suppression, nutrient cycling, and climate regulation) (Bommarco et al., 2013; Geertsema et al., 2016). Ecosystem services and functions have particular relevance in Sub

Saharan Africa (SSA), where the majority of the population live in rural areas and rely on ecosystem services and functions for their living through smallholder farming, pastoralism and fisheries (Egoh et al., 2012). Despite the potential of ecological intensification to improve food production systems in smallholder agricultural systems in SSA, it has rarely been seriously addressed in the context of smallholder farming systems of rural Africa (Tittonell & Giller 2013) and its research remains limited in SSA (Struik & Kuyper, 2017). Hence, there is a need to understand how ecological intensification technologies can be leveraged in smallholder farming systems to improve food security in their heterogeneous socioeconomic and environmental circumstances in South Africa. This paper aims to develop pathways to improve agricultural productivity among smallholder farms in rural South Africa. In this study, we explored two hypotheses,

(i) stratification of farm types according to farm size, farm resource endowments, production objectives and source of household income could support a more tailored approach to develop ecological intensification of technologies adapted to different farm types in smallholder agriculture; and

(ii) understanding of farm type constraints, challenges and solutions could be an entry point to identify, link and harness specific ecosystem services to improve agricultural productivity through tailored ecological intensification technologies

We use this analysis to propose options for ecological intensification that may be suitable for the different types of smallholder farms in semi-arid South Africa.

## 3.2. Materials and methods

### 3.2.1 Study area

South Africa has a dual agricultural system, with a well-developed commercial agricultural system that contributes significantly to national food security. The second type is a less developed and less resourced agriculture occupied by smallholder farmers. This study was conducted in Ha Lambani, a village in Vhembe District in Limpopo province South Africa. Limpopo province is the fourth largest province in South Africa (Statistics South Africa, 2015). It has the highest population growth rate of 3.9 % per annum and 90 % of the population live in rural areas (De Cock et al., 2013). The study site typifies smallholder farming areas that are less developed and less resourced and that can, in similar forms, be encountered in other villages and districts in Limpopo province. Smallholder agriculture accounts for 70 % of the farming activities in the district whilst the other 30 % is commercial agriculture. According to

Mpandeli & Maponya (2014), the main contributor to employment and livelihoods in the Vhembe District is agriculture.

The district is situated in a semi-arid area is frequently affected by dry spells (often developing into severe drought), and experiences severe water shortages from May to August. Most commercial farmers depend on irrigation systems for farming while smallholder farmers rely on seasonal rainfall, which is normally received from November to March. The district average rainfall is low and variable (ranges from 246 mm to 681 mm per annum). Temperatures range from approximately 5˚C in winter to around 35˚C in summer. Soils in the district are variable tending to be sandy, loamy and clayey in different areas within the district. The soils are mainly developed on basalt, sandstone and biotite gneiss and are generally of low inherent soil fertility. The smallholder farmers predominantly grow maize, legumes, and some vegetables for their consumption, with any surplus sold to neighbours or relatives. Rain-fed maize crop yields are generally poor due to low and erratic rainfall as well as poor soil fertility.

### 3.2.2 Theoretical and conceptual framework

An understanding of smallholder farming systems cannot be achieved without considering the wider socio-economic context in which these smallholder farmers live and operate. In the context of smallholder farmers in sub Saharan Africa (SSA), when analysing farming systems across Africa bewildering complexity is faced (Giller et al., 2011). Therefore, different analytical methods can be employed, which combine on farm participatory research, farm typologies, experiments and modelling tools to identify pathways towards intensification of smallholder farm systems. Describe, Explain, Explore and Design (DEED) is one approach that proposes a logical sequence of activities for researchers and farmers to co-learn in identifying suitable technologies for a specific context. For this study, the Describe, Explain, Explore and Design (DEED) approach (Giller et al., 2011) is used as a theoretical basis to develop our conceptual framework, as it focuses on identifying suitable technologies for specific contexts and farm types. The steps in what we call the DEED approach are used to 1) describe (D) current production systems and their constraints through ex-ante analysis of the options and the prerequisite conditions; 2) explain (E) the consequences of current farmers' decisions on resource allocation through testing and analysing options using theory, on-farm experiments and modelling to understand current practices and systems; 3) explore (E) options for improving agricultural productivity through analysing trade-offs, opportunities and constraints to adoption of technologies at multiple scales through scenario analysis; 4) design

(D) together with farmers, by proposing and testing new configurations of cropping systems, farm, and farming systems and landscapes that can contribute to ecological intensification of smallholder agriculture systems. In this study, the DEED conceptual framework is well suited, as the methodology facilitates an approach, where knowledge gained from the research can lead to positive action relevant to the actual conditions and concerns of the stakeholders involved. In addition, various methods can be used in the DEED research cycle. In this study, a combination of detailed characterisation with local experts, surveys and participatory approaches were applied. The study uses the DEED approach by combining both qualitative and quantitative methodologies to describe and explain the structure of the farming system and understand differences in perspective related to constraints and solutions perceived by a group of farmers in the study area. The farmers' direct involvement improves the understanding of the heterogeneity of farming systems and decision making in general. We use the constraints and challenges to identify and link specific ecosystem services to explore the potential of ecological intensification options in improving agricultural productivity. Overall, our conceptual model fits the purpose of the study by characterising the farming system heterogeneity and foregrounding where varying challenges help better understand the context of the farming system under study. This directly assists in targeting appropriate technologies and guides the development of ecological intensification pathways tailored to smallholder agriculture.

### 3.2.3 Identifying different smallholder farm types in Ha Lambani

In the context of the project, to identify farm types, we used expert knowledge. An introductory meeting was held with the senior agricultural extension workers to request cooperation from the field-based extension workers and to present the research objectives. These were to (i) classify farms and farmers in the study area, (ii) unravel and assess farming system performance and efficiency levels, (iii) identify challenges and constraints and (iv) identify opportunities to sustainably intensify farming systems through ecological intensification technologies. Five key informants, field-based agricultural extension workers based in the study area were identified by the senior agricultural extension workers. Four of the agricultural extension workers specialised in crops and one specialised in livestock. The agricultural extension workers were informed that the objective was to classify smallholder farmers based on predominant socio-economic characteristics, resource endowments and production objectives. Thereafter, based on their expert knowledge, in depth experience of local communities and structure of the local farming system and landscape, local agricultural extension workers identified the most important sources of variation among farms and helped define three farmer types, given those variables (Table 3.1). The key differences among the farm types were production objectives and resource endowments. According to Kuivanen et al., (2016) the expert based approach for classifying farmers captures context specific aspects of farm complexity and has potential to enhance local relevance and socio-cultural sensitivity aspects of interventions. Nevertheless, the degree to which an expert-based approach based on these variables can predict actual behaviour in the context of rural development has not been proven. The main limitation of the expert-based approach in classifying farmers and farms is that the reliance on local experts as sources of information is not enough for comprehensive understanding and analysis of complex and diverse farming systems, as it can be potentially misleading and biased. Therefore, the expert-based approaches need to be combined with participatory and statistical approaches to retain objectivity and reproducibility. Acknowledging this limitation, this work is only able to complete the initial steps of establishing a baseline to guide in exploring potential strategies to promote or foster ecological intensification.

*Table 3.1: Variables used to construct the farm types*

| ***Variable*** | ***Type 1: Cereal and livestock farms*** | ***Type 2: Horticultural farms*** | ***Type 3: Off-farm income-based farms*** |
|---|---|---|---|
| *Household size* | 5 | 3 | 5 |
| *Average number of children* | 3 | 1 | 3 |
| *Age of household head (years)* | >60 | 18-35 | 35-60 |
| *Level of education of household head* | No education | Grade 12 | Grade 12 |
| *Major source of income* | Farming | Farming | Salaries/ part time jobs |
| *Other sources of income* | Grants & remittances | Grants | Farming |
| *Average farm size* | >2 ha | <1.5 ha | 1.5 -2 ha |
| *Average size of land cultivated* | 1.5 ha | 1 ha | 1 ha |
| *Major crops grown* | Maize | Vegetables | Maize /vegetables |
| *Minor crops grown* | Legumes /vegetables | Green mealies | Legumes |
| *Average maize yields (t/ha)* | 1 t/ha | 0.25-0.5 t/ha | >0.5 t/ha |
| *Number of cattle* | 15 | 0 | 5 |
| *Number of goats* | 5 | 0 | 5 |
| *Use of inorganic fertiliser* | 1-3 x 50 kg bags | 4-8 x 50 kg bags | 1-3 x 50 kg bags |

### 3.2.4 Identifying challenges, constraints and opportunities for ecological intensification

We used a snowball sampling approach to identify farmers representing each of the three farm types, to take part in face to face interviews. Snowball sampling is arguably the most widely employed method of sampling in qualitative research in various disciplines. Snowball sampling is a non-random approach for locating information-rich key informants to participate in a study (Palinkas et al., 2015). In this approach, the researcher accesses informants the through contact information that is provided by other informants. Using this approach, agricultural extension officers identified 40 potential interviewee farmer respondents to represent the three farm types. We interviewed 40 farmers, of which 16 were cereal and livestock-based farmers, 7 horticulture-based farmers and 17 off farm income-dependent farmers. Face to face questionnaire-based structured interviews were conducted with the help of the agricultural extension workers, who assisted in the translation of the questions and farmer responses. The number of respondents was limited by project resources and farmers' lack of availability during the interview period. Although a small sample, the in-depth nature of the interview conducted has resulted in an informative quantitative and qualitative insight into farmers' views. The interviews sought information on the estimates of farm size, cropped area, types of crops grown, estimates of yields obtained, crop preferences and production objectives. Farmers were asked to identify major constraints and challenges to their current crop and livestock farming practices. Farmers' perceptions on their potential solutions to their production constraints and objectives were sought by means of open-ended questions. Furthermore, through discussions with farmers, we could identify key ecosystem services important to different farm types in the study area. Owing to the small sample size of farmers interviewed in each class, descriptive statistical analysis was carried out on the survey data.

## 3.3. Results

### 3.3.1 Farm types and household characterisation

Field based agricultural extension workers identified three types of farms in Ha Lambani. The farms overlapped in many characteristics but differed in their main source of income. The farm types identified were namely: (1) the cereal and livestock-based, (2) the horticulture-based and (3) the off-farm income-dependent farms. Table 3.1 shows the variables used to build the typology.

**Type 1: Cereal and livestock-based farms**

The cereal and livestock-based farms were large farms (averaging more than 2 ha), with elderly household heads (60 years old or more). Maize is the most cultivated crop, whereas legumes and vegetables are minor crops in this category. Livestock is a determinant factor, with farms rearing mainly cattle and goats (10-15 cows and 5 goats on average) on a free range grazing system. Cereal and livestock activities contribute most to the household income (75%), while social grants and remittances come as a complement (25%).

**Type 2: Horticulture-based farms**

The horticulture-based farms are small, often less than 1.5 ha. They comprise mainly young household heads ranging from 18 to 35 years of age. Leafy vegetables such as spinach are mostly grown and maize (green mealies) is cultivated as a minor crop. Farmers in this category did not own livestock. Income from horticultural activities is the major source of household income.

**Type 3: The off-farm income dependent farms**

The off-farm income-dependent farms are average sized farms, often between 1.5 and 2 ha. The household heads are mainly farmers aged between 36 and 60 years. They mostly grow maize and vegetables. Legumes such as cowpea, groundnuts and bambara groundnut are grown as minor crops. They own a small herd of livestock biased towards ruminants (5 cows and 5 goats on average). The largest household income comes from salaries and part-time jobs they engage in their local communities, complemented in small portion by agricultural activities.

### 3.3.2 Farm types and farming system patterns

The results of the survey are summarised in Table 3.2. The interview results revealed an estimated average farm size of more than 2 ha for Type 1, 1.5 to 2 ha for Type 3 and less than 1.5 ha for Type 2, with Type 1 farms exhibiting the largest average cropped area of 1.5 ha. Type 2 had the smallest average cropped area of less than 1 ha. Maize was the major crop grown by Type 1 and 3 farmers, although no crop yields records were available in almost all the households interviewed. The farmers estimated that the yields obtained were very poor averaging 1 t/ha and just above 0.5 t/ha for Types 1 and 3, respectively. All farm types were involved in vegetable production with only Type 2 farms growing vegetables as their major crops and primarily as a cash crop and a major source of income. The results indicated that Type 2 farmers preferred to grow high value horticultural crops on a small area throughout the year. Types 1 and 3 farmers are involved in the production of legumes (mainly cowpeas, groundnuts and bambara groundnut) and vegetables on a small scale, mainly for household consumption and rarely as cash crops. Furthermore, results from the interviews further affirmed that Types 1 and 3 farms are involved in livestock production with Type 1 farms possessing the most animals and the largest cattle herds. Type 2 farmers did not possess any cattle or small ruminants, citing lack of capital to purchase as well as lack of resources and labour to rear the animals. Type 2 farmers generally lack access to animal traction, resulting in reduced crop area.

Chemical input use in all farm types was generally low with Types 1 and 3 farmers applying between 1-3 bags of 50 kg inorganic fertilisers per hectare. Type 2 farms' use of chemical inputs was higher when compared to the other farm types and they applied an average of 8 bags of 50 kg inorganic fertiliser per hectare. This is because horticultural crops are input demanding and the farms lack of livestock means lack of organic fertilisers to complement soil fertility. Type 2 farmers highlighted that they relied on sub-optimal application of inorganic fertilisers for soil fertility improvement and sub-optimal application of agrochemicals for crop protection against pest and diseases. Although income from social grants helped Type 1 (cereal and livestock-based) farmers to acquire some farming inputs, Types 1 and 3's low use is mostly due to fertilizer and herbicides cost and access. Hence Types 1 and 3 farms relied on traditionally low resource input methods of agriculture.

Type 1 farmers rely mostly on farming (sale of agricultural produce and livestock) for income, although they are recipients of government social grants of the elderly and remittances from their children located in urban areas. Type 2 farmers rely on producing and selling high value horticultural products, although most are also recipients of child support grants. Type 2 farmers also highlighted that financial returns from crops like maize, cowpeas and groundnuts were often not worth the effort when set against the risks of producing those crops under rainfed conditions. Type 3 farms often engage in non-farm based remunerated activities such as craft making, bead work, carpentry, brick moulding, traditional beer selling and seasonal work, for household income. They engage in agricultural activities to supplement household income.

### 3.3.3 Farmers' perceptions of their current challenges and constraints

The interview results revealed that all farm types faced varying challenges and constraints in their agricultural activities, although poor seasonal rainfall distribution, low precipitation amounts, and lack or poor irrigation infrastructure (dilapidated) were common and major constraints among all the farm types. A significant proportion of Type 1 farmers also cited poor access and high costs of inputs, especially fertilizer, as a major constraint. Furthermore, they pointed out shortage of livestock feed, especially during the dry season and drought years, leading to either loss of livestock or crop damage by livestock reaching for feed, or both. Type 2 farmers cited high incidences of pests and diseases in their horticultural crops as a major challenge in their cropping fields. In addition, Type 2 farmers pointed out post-harvest losses and poor access to markets as major constraints. Furthermore, they highlighted poor access to pesticides, despite having limited financial resources. Mechanisation and draught power were their major challenges to increasing the area under crops. Type 3 farmers considered lack of access to inputs, lack of livestock feed during the dry season and drought years and damage of crops by livestock during the dry season as significant constraints.

### 3.3.4 Perceived solutions to farming constraints and challenges

All farmers in all farm types proposed government subsidies on agricultural inputs and improved irrigation infrastructure as potential sustainable solution to their challenges and constraints. Type 1 farmers proposed access to drought tolerant maize and legume varieties to help achieve higher yields. The establishment of paddocks was cited to allow their livestock to graze. Lastly, they highlighted the need for access to financial loans or grants as they would facilitate the acquisition of much needed irrigation systems, machinery or inputs for improved crop production. Type 2 farmers see quick access to markets and proper post-harvest handling facilities as direct improvements to cater for their perishable horticultural products. Furthermore, they pointed out the need for training in local horticultural crop production skills. Type 3 farmers, for whom farming is supplementary to off-farm income, consider that fencing of fields and establishment of paddocks for their livestock to graze would greatly improve their agricultural activities.

### 3.3.5 Identification of ecosystem services as a framework for targeted ecological intensification

Based on the survey results, three key ecosystem services were identified for each farm type to improve agricultural productivity (Table 3.2). All farm types identified soil and water conservation as a key ecosystem service they would benefit from towards increased agricultural production. Type 2 farmers (horticulture-based) further emphasised the need for improved water quality which would translate into improved horticultural production. This is because poor quality irrigation water tends to impact both directly and indirectly on soil characteristics (physical, biological and chemical). A significant proportion of Type 1 (cereal and livestock-based) and Type 3 (off-farm income-dependent) farmers identified, nutrient recycling as a key ecosystem service needed to improve soil fertility in their farming landscapes. Type 1 farmers further emphasised the need for provisioning ecosystem services that improve the availability of forage and fodder for improved livestock production. Type 2 and Type 3 identified pest and disease suppression as a key ecosystem service needed to reduce crop losses.

*Table 3.2: Challenges and constraints, solutions and the key supporting and regulating ecosystem services needed to implement ecological intensification in the three farm types in Ha Lambani, Vhembe District South Africa*

| ***Farm type*** | ***Type 1: Cereal and livestock-based farms*** | ***Type 2: Horticulture-based farms*** | ***Type 3: Off-farm income-based farms*** |
|---|---|---|---|
| ***Initial Problems*** | Poor rainfall | Poor rainfall | Poor rainfall |
| | Poor/ dilapidated irrigation infrastructure | Poor/ dilapidated irrigation infrastructure | Limited/ no irrigation infrastructure |
| | Shortage of livestock feed | Limited draught power & mechanisation | Shortage of livestock feed |
| | High input costs | Limited access to inputs | Limited access to inputs |
| | Damage of crops by livestock | Poor access to markets | Damage of crop by livestock |
| | Limited access to inputs | High post-harvest losses | Labour constraints |
| | | | |
| ***Proposed solutions*** | Government subsidies & access to finance | Government subsidies & access to finance | Government subsidies & access to finance |
| | Rehabilitation of irrigation infrastructure | Rehabilitation of irrigation infrastructure | Access to irrigation infrastructure |
| | Access to drought tolerant varieties | Access to markets | Fencing of fields |
| | Fencing of fields | Technical know-how and skills training | Paddocking of livestock |
| | Paddocking of livestock | Proper post-harvest handling training and facilities | |
| | | | |
| ***Ecosystem services related issues*** | Soil and water conservation | Soil and water conservation | Soil and water conservation |
| | Nutrient recycling | Pest suppression | Nutrient recycling |
| | Forage and fodder | Improved water quality | Pest and disease suppression |
| | | | |

## 3.4. Discussion

### 3.4.1 The diversity of the farm types and farming system patterns

The study performed two iterations of the DEED research cycle, namely characterisation and assessment. Firstly, the characterisation led to the development of farm typologies. The typologies developed in this study combined both expert knowledge and participatory approaches to unravel the complexity and diversity in heterogeneous smallholder farming systems. The clear differentiating factors identified among farm types were farm size, the farm objective and the major contributor to household income, which resulted in three farm types (Table 3.1). Results have shown that farming systems are driven by different farming objectives that, in turn, are shaped by various factors such as agro-ecology, markets, institutions, and traditional land tenure and inheritance systems. These different objectives influence the different farming system patterns exhibited in different smallholder farm types. Of these farm types, we found that Type 2 (horticulture-based) farms were well distinguished from Type 1 (cereal and livestock-based) and Type 3 (averaged sized off-farm income-dependent farms). The latter two types showed intermediate properties, hence less distinctiveness.

Cereal and livestock-based farm types have capacity to grow the following cereal crops namely maize, sorghum and millet cereal and leguminous crops such as cowpea, groundnuts and bambara nuts, use best agronomic practices, including early planting, weeding and application of organic manures/ fertilizers, all of which enhances the yield difference when compared with off-farm income-dependent and horticulture-based farm types, which have limited land and labour. Furthermore, the rearing of livestock is very important for satisfying food security in South Africa. Livestock represents the most important store of value for farmers and the wealth of a household can be measured by the number and type of animals owned (Chaminuka et al. 2014). Livestock herds owned by Type 1 (cereal and livestock-based) farmers and Type 3 (off-farm income-dependent) farmers provide animal traction and manure, thus putting these farmers at an advantage in terms of agronomic performance, improved soil fertility and planting larger areas when compared to Type 2 (horticulture-based) farmers.

Farmer income affects most decisions, including those regarding the adoption of farming practices which can require financial investment and can reduce short term profitability. The extension workers we consulted in Ha Lambani segregated on-farm and off-farm income because the source of income influences its connection to farm business investment decisions. Type 1 farms rely mostly on farming (sale of produce and livestock) for income although they are recipients of government social grants of the elderly and remittances from their children located in urban areas. Financial and resource limitations in Type 3 farms may often induce a shift in livelihood strategies towards a higher dependence on off-farm income. Type 3 farms often engage in non-farm-based strategies such as craft making, bead work, carpentry, brick moulding, traditional beer selling, and seasonal work as hired labour to supplement household income as mentioned above. This influences decision-making, cropping patterns and farming practices. In semi-arid environments, there is only a narrow window for obtaining the right balance of agronomic practices that facilitate high yields. Engagement in non-farm activities limits the amount of time Type 3 farmers engage in cropping activities, resulting in the delay of farming operations leading to poor yields. These findings suggest income from farming, off-farm income generating activities and social grants play an important role in the livelihoods of people in the study area. This is because the income from these activities determines the livelihood strategies to be adopted by the households.

A very small proportion of the rural population in Ha Lambani makes a significant income from growing crops such as maize, cowpeas and groundnuts. This has led the few young people involved in farming to specialise in horticultural crops, which are of high value with high returns for income, in addition to the child support grants they receive from the government. Hence, Type 2 farms are horticulture-based and derive most of their income from the sale of horticultural produce. An important finding of this study that agrees with other studies is that very few young people want to engage in cereal and legume crop production in rural areas. This is because agriculture is often perceived as an occupation of the poor, hence young people have little desire to be involved in it (Leavy & Hossain, 2014). Furthermore, these findings highlight the importance of taking a comprehensive survey of the production envelope, rather than focusing only on blanket recommendations when targeting and tailoring agricultural interventions to local contexts. Technological interventions, development strategies, and policies to address the problem of poor productivity and reduce poverty in smallholder agricultural systems must be designed to target socially diverse and spatially heterogeneous farms and farming systems in rural South Africa.

### 3.4.2 Perspectives on the underperformance of farming systems

Secondly, the DEED approach allowed assessment of current farming systems performance which led to the identification of constraints and challenges. As shown by the results, the different farm types tend to experience the same major constraints. Poor seasonal rainfall distribution and amount, and poor or lack of irrigation infrastructure were common constraints among all farm types. This is because most smallholder farmers, if not all farmers, in Ha Lambani depend on rainfall for their agricultural activities. The unreliable and limited availability of water and infrastructure for irrigation increases reliance on rainfall and its consequent unpredictability affects farmers' ability to decide, for instance, what, when and where to plant their crops and make other farm related decisions. The low mean annual rainfall of 500-800 mm, high annual evaporation of 2000-2500 mm in Ha Lambani (Botha et al., 2014) and recurring droughts indicate most seasons experience crop water stress. Limited irrigation infrastructure (dilapidated or malfunctioning), further exacerbates the problem.

The limited access to seed, tillage and irrigation equipment, fertilizers and agrochemicals due to both physical and financial constraints of poorer households translates into a limited capacity to diversify their livelihood strategies by growing either more water efficient crops or higher return varieties. In many aspects of smallholder production in Ha Lambani, declining soil fertility is a major constraint as well. Although Type 1 and Type 3 farms relied on animal manure for soil fertility improvement, the low nutrient content of manure means larger quantities are needed. Consequently, the average quantity of manure applied which ranged from 2-5 t/ha was insufficient to achieve high yields. Furthermore, manure alone may be an unsatisfactory source of nutrients, especially for nitrogen and phosphorus, which are required in large quantities, and therefore rarely provided sufficiently. It has therefore been suggested by Zingore et al. (2008) that to sustain high crop yields, manure may need to be combined with nitrogen fixing legumes in resource constrained low input farming systems.

The importance of weed, insect pest and disease problems amongst Type 2 farmers arise from the impact those have on their livelihoods due to the susceptibility of horticultural crops to these biotic stressors. Although Type 2 farmers acknowledged that pests and diseases were a problem, most farmers had poor knowledge of diseases affecting their vegetable crops. Smallholder farmers in Ha Lambani operate in a resource constrained environment in terms of both financial and physical access to inputs such as pesticides and fertilisers. Furthermore, the demand for constant labour, herbicides, and pesticides, and the lack of a strong technical resource base and skills for crop protection, further exacerbate the problem. Technical agronomic and horticultural information relating to cultivar and seed choice, soil fertility, water management, and pest management using cultural, biological and chemical methods is also still lacking in rural South Africa (Mpandeli & Maponya, 2014). The smallholder horticultural sector, therefore, requires support in the form of improved access to technical pest management information. Among other options, ecological intensification can play an important role in managing pests and diseases through biological control, such as the use of natural enemies, plant extracts and other sustainable integrated pest management (IPM) methods that either repel the insect pests or breakdown their life cycles of both insect pest and diseases.

Despite numerous efforts to promote the production of high value cash crops in smallholder agriculture as a crucial step for improvement of food security towards solving food security, most famers including Type 2 farmers, cannot easily access cash crop markets to sell their produce. The access constraint is amplified by lack of or poor storage, facilities resulting in severe post-harvest losses in crops such as tomatoes, and most smallholder farmers remain excluded and marginalised from profitable markets and information. Consequently, even those who can produce surpluses remain trapped in a poverty cycle, and often these farmers are forced to sell their produce at lower prices to unscrupulous buyers, who dictate accessible market prices.

The low quality and quantity of available forages during the dry season is a major constraint for improved livestock production in Ha Lambani. As in many rural areas of South Africa, the available grazing is not generally sufficient to meet the maintenance requirements of grazing animals (Beyene et al., 2014) during dry periods. Although Type 1 (cereal and livestock-based) and Type 3 (off-farm income-dependent) farmers use different feed supplements during the dry season and drought years, issues of availability, quantity, and quality of feed remain and affect them as well. Lack of feed is mainly attributed to shortage of grazing land, lack of improved forage technologies and lack of awareness of other feed technologies. The introduction of improved forage technologies and improved feeding systems adapted to the existing land use is necessary to reduce feed availability challenges. Other livestock production challenges in the area, such as poor access to extension officers, who in turn, are often overcommitted and under-resourced, and poor knowledge of pasture and animal management should be addressed simultaneously to fully realise the potential of intensified livestock production.

Among the solutions mentioned by all the farm types to the above-mentioned constraints and challenges were increased government subsidies for agricultural inputs and rehabilitation or improvement of existing irrigation infrastructure. This confirms that most of the agricultural activities are currently low input systems relying on supporting and regulating ecological processes. Therefore, the improvement of smallholder agriculture through improved ecologically based management strategies may indeed represent a viable and sustainable pathway to increasing resilience and productivity despite limited support from government to smallholder farmers.

### 3.4.3 Opportunities for improved production through ecological intensification

The limited government support combined with large farming systems diversity makes ecosystem service enhancement critical for building resilience and improving food and nutrition security for smallholder farmers in SSA. The farmer interviews identified four key ecosystem services with higher potential to improve agricultural productivity in Ha Lambani. All farm types identified soil and water conservation as a key supporting ecosystem service to increase agricultural production. Following recurrent severe water shortages for both domestic and agricultural sectors, better management of supporting ecosystem services linked to soil and water conservation offers clear potential to increase agricultural production. This presents tremendous opportunities for ecological intensification practices and interventions such as minimum tillage, mulching, and water harvesting among others (Kassam et al., 2014), which make use of natural capital within the soil. For instance, Thierfelder et al., (2015) collated and summarised evidence on soil water storage effects of minimum tillage, and various soil amendments in smallholder agriculture in southern Africa. Horticultural crops (Type 2 farmers) are highly dependent on water quality and already use some form of irrigation. They would, therefore, benefit directly and highly from a clean and constant water supply.

A significant proportion of the farmers interviewed identified nutrient recycling as a key supporting ecosystem service needed to improve productivity. This emerges from high nutrient demanding main cereal crops, and Type 1 (cereal and livestock-based) and Type 3 (off-farm income-dependent) would benefit from nutrient recycling ecosystem services improving soil fertility. Ecosystem services and processes that increase soil fertility can critically improve common soil fertility depletion resulting from low fertilizer use and high rates of nutrient mining among smallholder farmers in South Africa and in the region (Zingore, 2016). This presents an opportunity for ecological intensification through practices and interventions that promote ecological processes and biological diversity in those farming systems. Supporting and regulating ecosystem services and processes, such as intercropping and crop rotations, can be incorporated into cropping systems, such that production is improved, nutrient flow and soil fertility are enhanced and, at the same time the need for external inputs such as fertiliser, is reduced.

The availability of forage and fodder was identified as key provisioning ecosystem services they would benefit from to improve livestock productivity. Currently, low quality and quantity of feeds can be improved through ecosystem services and processes that provide forage and fodder to Type 1 (cereal and livestock-based) and Type 3 (off-farm income-dependent) farms. Although ecological intensification is widely documented in field crops, it is less well documented for animal production (Loucougaray et al., 2015; Dubeuf et al., 2018). However, it presents an opportunity for the development and operationalisation of ecological processes and services in resource constrained smallholder livestock systems. To foster such a development and operationalisation, we propose the introduction of improved forage technologies, such as forage legumes and crop residues that can fit into the existing land use system coupled with improved feeding systems.

Lastly, Type 2 (horticulture-based) farmers identified pest and disease suppression as key regulating ecosystem services for improvement. Weeds, insects and pathogen infestation are a major challenge to their horticultural farming activities, both through crop sensitivity and labour demand and input cost of treatment application. In Ha Lambani where farmers' access to and ability to purchase chemical pesticides are limited, ecosystem services that enhance natural pest control can significantly improve quality and quantity produced. Dicks et al., (2016) summarised evidence that identified practices that enhanced natural pest control in agriculture. In this regard, ecological intensification approaches that make use of biological processes (such as the use of natural enemies, push-pull systems, or crop rotations, among others) to regulate pest population would enhance pest suppression and contribute to crop protection. There is quite clear evidence of those interventions' efficiency, especially the push-pull systems (Khan et al., 2008; Midega et al., 2014). These low costs and environmentally friendly crop protection strategies are particularly adapted to rural resource constrained farms.

## 3.5. Conclusion

Plans for agricultural intensification need to consider the differentiated patterns of livelihoods and landscapes rather than considering whole areas as homogenous. The study reinforces the heterogeneity of farming systems, even among smallholder farmers in a relatively small area of Ha Lambani, South Africa, which might be considered homogenous from a policy perspective. The farms are clearly different in terms of their production objectives, and biophysical and socio-technical conditions. For agricultural intensification to take place in such heterogeneous smallholder agricultural areas, the diversity of constraints and opportunities existing across farm types needs to be addressed, by offering specific and adapted agricultural enhancing technologies and interventions. Our study identified a few critical challenges, which can be successfully addressed by the development of specific ecosystem services. From the findings presented in this paper, ecological intensification needs to exploit several services, and farms will benefit more from harnessing specific adapted ecosystems services to improve agricultural productivity.

Beyond Ha Lambani, for improvement of smallholder agricultural productivity and livelihoods, we argue the need for agricultural intensification. Ecological intensification, due to its stability and limited costs, seems a promising pathway to intensify smallholder farming systems in rural areas. One means to achieve this is by identifying, developing and harnessing those needed ecosystem services to enable its implementation. Furthermore, research and specific attention should be devoted to the environmental and social implications of proposed interventions. This will enable the evaluation of synergies and trade-offs if ecological intensification is to be scaled to other environments and regions. This will enable appropriate ecological intensification options to be identified to enhance agriculture productivity, where agricultural and farming systems, such as in smallholder communities, are so diverse that the one size fits all approach has the potential for only partial improvement.

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# CHAPTER 4

# Enabling acceptance and use of ecological intensification options through engaging smallholder farmers in semi-arid rural Limpopo and the Eastern Cape, South Africa

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# Abstract

Ecological intensification is being promoted to address both global challenges of food security and environmental sustainability because of its potential to improve yields, adapt and mitigate the effects of climate variability and change. Despite its great potential, smallholder farmers continue to shun it. Apart from this, limited research has been conducted focussing on its acceptance and use in smallholder sub Saharan African agricultural systems. In this study, a qualitative approach using the Unified Theory of Acceptance and Use of Technology (UTAUT) four constructs (performance, ease of use, social influence and enablers) was used to assess behavioural intention to accept and use ecological intensification options. A total of 97 smallholder farmers from diverse farm types in rural Limpopo and the Eastern Cape, South Africa participated in focus group discussions to assess behavioural intention to accept and use ecological intensification options. Smallholder farmers revealed that they were exposed to a plethora of ecological intensification options. However, acceptance and utilisation of these options were low, mainly due to lack of knowledge, germplasm and technical support. The four constructs of the UTAUT framework revealed locally relevant knowledge that must be considered to enable acceptance and use of ecological intensification options.

Key words: ecological intensification, unified theory of acceptance and use of technology, smallholder farming systems

## 4.1 Introduction

South Africa as a nation is regarded food as secure. However, most rural households that depend on agriculture as a livelihood are food insecure (De Cock et al., 2013; Musemwa et al., 2015). Debates on how to revitalise smallholder agriculture to improve food security in disadvantaged rural South African communities are gaining momentum (Thamaga-Chitja and Morojele 2014). Around four million smallholder households are still largely confined on 13% of the country’s land (Louw, 2013). Much of this land is severely overcrowded (Edward & Cousins 2005), with arable land holdings averaging between 0.5 to 1.5 ha per household (Aliber & Hart, 2009). As in many African countries, South African smallholder farmers practice rainfed subsistence agriculture (Thamaga-Chitja & Morojele 2014), in areas with low agricultural potential. It is anticipated that these areas will be severely impacted by the negative effects of climate change and variability (Turpie & Visser 2015). Cropping takes place in gardens and demarcated fields, consisting of staple and vegetable crops for household consumption. The farms are not well developed or resourced and rely on traditional methods of production generally characterised by low input-low production systems (Thamaga-Chitja & Morojele 2014). As a result, food insecurity is a challenge that persists in these smallholder farms (Masipa, 2017).

According to Food and Agriculture Organisation (FAO) (2015), South Africa as a nation achieved its target of halving undernourishment and food insecurity by 2015. Yet, the lack of sustainability in both the commercial and smallholder farming sectors is increasingly worsening (Laan et al., 2017). Also, several studies have shown that smallholder farms are shrinking in size due to increasing population densities in rural areas (Jayne et al., 2014). Smallholder farming areas are associated with environmental degradation and environmental conditions within the smallholder areas continue to deteriorate and worsen because of continuous cropping of fields, land degradation due to natural and anthropogenic factors, and poor government support for smallholder farmers, amongst other causes, are all contributing to unsustainable forms of agricultural intensification (Timm Hoffman, 2014). Unavailability of land for cropland expansion in these areas (Aliber, 2003), means that South Africa should adopt a sustainable approach to intensify smallholder food production systems (Laan et al., 2017). If not done, current and future generations are at risk of household food insecurity (De Cock et al., 2013). The scarcity of farmland, high levels of environmental degradation and increased vulnerability of smallholder farmers to climate variability and change calls for new pathways to sustainably improve and intensify food production systems. Mismanaged agricultural intensification might compromise food production systems and food security, leading to increased poverty and environmental degradation. This situation calls for the development of appropriate methods of intensification as well as enabling conditions for successful implementation.

Ecological intensification is being recognised for enhancing ecosystem services and improving crop yields (Bommarco et al., 2018). Ecologically intensified cropping systems have shown a predominantly win-win situation when compared to conventionally intensified cropping systems, particularly in terms of maintaining or increasing yields and ensuring the provision of ecosystem services to ensure environmental sustainability (Garbach et al., 2017). Smallholder farming systems in SSA are mostly low input in nature, highly dependent on local resources, varieties, breeds and family labour to produce food (Sheahan & Barrett, 2017). Most of the farming systems have remained ecological, maintained and enhanced by ecosystem services that either support or regulate productivity and through location-specific indigenous knowledge, which is still embodied in many smallholder agricultural systems in many places in SSA (Tittonell & Giller, 2013; Mapfumo et al., 2016). Although there are many ecological intensification options associated with yield gains, African smallholder farmers are resource constrained and face important trade-offs in resource allocation due to the interconnectedness of farming systems (Tittonell et al., 2009). Smallholder farmers may not benefit from the potential yield gains emanating from the options because they come with varying costs, socio-economic impacts and also require conducive environments for their uptake (Tittonell & Giller, 2013; Harris & Orr, 2014). These pressures shape farmers' decision making in accepting and using particular agricultural technologies, as they may have both short and long-term consequences on farm livelihoods. Thus, the implementation of ecological intensification options requires engaging with farmers and other stakeholders to understand trade-offs and synergies that arise among them. Smallholder farmers are heterogeneous in nature (Vanlauwe et al., 2016); they operate under various agroecological, socio-economic and market conditions (Caron et al., 2014). This makes it crucial to generate more information on the feasibility and viability of these options at farm scale.

This paper focuses on what can be done to improve acceptance and use of ecological intensification options in a context applicable to smallholder farmers. The specific objectives of this paper are therefore to understand farmer perceptions on:

(i) the relevance of ecological intensification options;

(ii) how ecological intensification could apply within the main livelihood and socioeconomic context; and

(iii) what can be done to enable implementation of ecological intensification?

To achieve the objectives specified above, the following questions were formulated. (i) How relevant are ecological intensifications options in their farming efforts? (ii) How well does ecological intensification apply and fit within the main livelihood and socioeconomic context of smallholder farmers? (iii) What can be done to enable the implementation of ecological intensification options in smallholder farming systems?

## 4.2 Materials and methods

### 4.2.1 Conceptual and theoretical framework

To address the above research questions, we took a qualitative and deductive path. We employ both farmer perceptions and theory to guide us, using key factors for enhancing technology use and acceptance. We identify options for ecological intensification and explore their relevance directly with farmers, utilising their lived experience of the context within which they are used in smallholder agriculture in South Africa. We then use and apply the Unified Theory of Acceptance and Use of Technology (UTAUT) conceptual framework (Venkatesh et al. 2003) to analyse and explore how ecological intensification options could be accepted and used in smallholder farming communities. The UTAUT framework has four key constructs that influence behavioural intention to use or accept a technology (namely, performance expectancy, effort expectancy, social influence, and facilitating conditions). In line with the UTAUT, performance expectancy is defined as the extent to which using a technology or practice will help improve productivity (performance) of a system; effort expectancy is the degree of ease or difficulty associated with the use of the technology or practice; social influence is the extent to which individuals perceive the usefulness of a particular technology due to others' persistent use of the technology; and enabling conditions are defined as the extent to which farmers believe that institutions, organisational and technical support exist to adopt the technology or practice (Venkatesh et al., 2003; Brown & Venkatesh, 2005). Various scholars have used the UTAUT conceptual model extensively to explain technology acceptance and use in agricultural systems (Rose et al. 2016; Beza et al. 2018). In this study, the model allowed rigour to be brought to the process of assessing acceptance and use of ecological intensification options by smallholder farmers, with an expectation for out-scaling.

### 4.2.2 Description of study regions

This study was conducted in the Eastern Cape and Limpopo Provinces of South Africa, respectively (see Figure 4.1). Both provinces are predominantly rural and classified as the poorest in the country. Compared to other provinces, they are also home to the largest number of smallholder farmers who are highly dependent on rainfed agriculture (De Cock et al., 2013; Musemwa et al., 2015). In addition, each smallholder farmer cultivates less than 2 ha on average. Maize, legumes and vegetables are the most commonly cultivated crops. Depending on their level of resource endowments, farmers own cattle, donkeys, goats, sheep, pigs and poultry. In the Eastern Cape Province, the study was conducted in Raymond Mhlaba Municipality in Amathole District. This district is a semi-arid area. The mean monthly temperatures in the district range from 6.2°C to 20.8°C in July and 17.2°C to 36.0°C in February. The district has a bi modal type of rainfall. Thus, it receives both summer and winter rainfall, with average annual rainfall not exceeding 600 mm. The months of October to March receive the most rainfall with 75 to 100 mm monthly averages, while May to September experience the least rainfall averaging 25 to 75 mm monthly (Chari et al., 2018). Climate change in this area is difficult to project (Wintola et al., 2017). The challenges posed by the highly variable semi-arid climate, compounded by factors such as poverty, inequality, and low income levels, among others, compromise the adaptive capacity of local communities (Chari et al., 2018).

In Limpopo Province, the study was conducted in Ha Lambani village of Vhembe District, which is about 180 km to the north of Polokwane at 22°58´S, 30°26´E. It is a semi-arid area found to the north of the Province. Rainfall in the area mostly occurs between October and January. In Ha Lambani, dry spells are common and frequent and often escalate into a severe drought (Ubisi et al., 2017). Climate projections for Vhembe district project that temperature is expected to increase by 1 to 3°C and rainfall will reduce by 5-10 % by 2050 (Department of Environmental Affairs and Tourism (DEAT), 2004). These stressors are another trait of importance to the study of acceptance and use, further highlighting the suitability of these communities for assessment of the potential of implementing ecological intensification options.

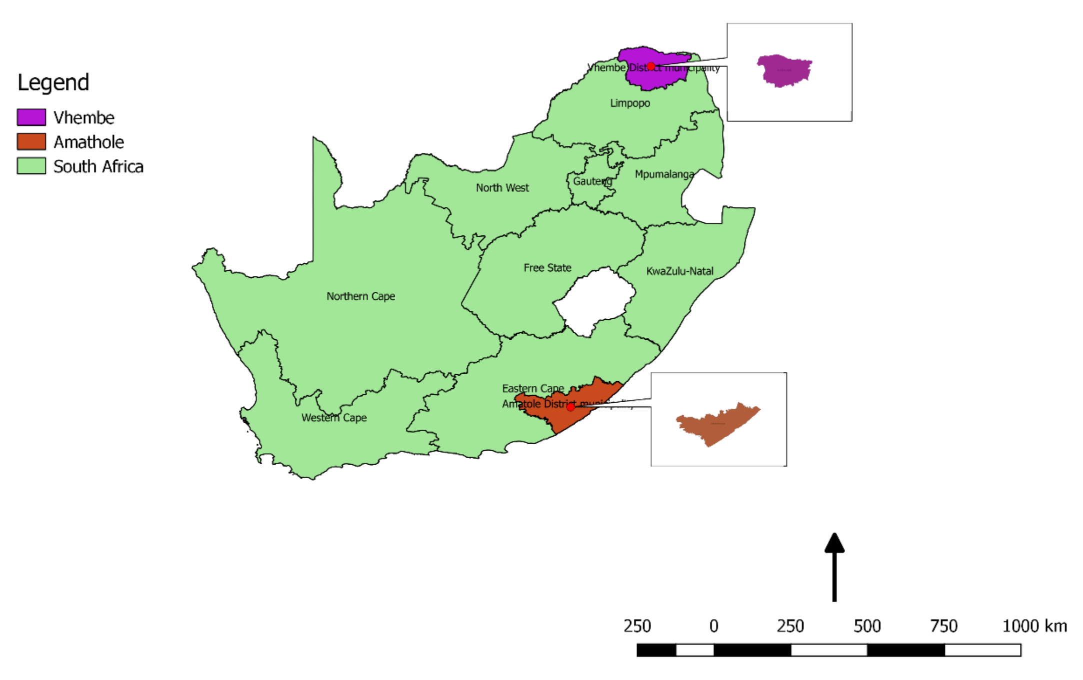

*Figure 4.1 Map of South Africa showing the location of the study sites in Limpopo and Eastern Cape Province*

### 4.2.3 Data collection methods and approach

This research was a qualitative case study analysis of ecological intensification options used by smallholder farmers in the study areas. The data collection approach involved two stages which were as follows:

(i) Stage 1: Identifying context specific ecological intensification options through literature review

(ii) Stage 2: Participatory action research through focus group discussions with local experts and smallholder farmers on the acceptance and use of ecological intensification options.

Our study was based on a mixed methodology centred on literature review and participatory action research (PAR) as data collection approaches. Participatory action research is being recognised as an alternative and practical method to identify needs, institutional capacity and to catalyse change in smallholder farming systems (Shames et al., 2016). Participatory action research is an approach in which project participants and stakeholders are involved in the formulation of research questions, research design, and methodologies, data collection and analysis (Méndez et al., 2017). We selected participatory action research in this case because it is context specific, participatory, it develops reflection based on interpretations made by the participants and is based on evidence gathered.

#### 4.2.3.1 Diagnosis and identification of potential ecological intensification options

A literature review was carried out to identify ecological intensification options common in South African smallholder agriculture. While this paper does not purport to be exhaustive in documenting every ecological intensification option practised in the smallholder agricultural sector in South Africa, it attempts to provide a comprehensive overview of ecological intensification options that can be used by smallholder farmers. These options/practices are listed in Table 4.1.

*Table 4.1 Description of ecological intensification options for smallholder farmers in South Africa.*

| Option | Description of the practice | Source |
|---|---|---|
| **Crop rotation** | A practice where different crops are grown one after the other on a field | Ndwandwe & Mudhara, 2008; Bloem et al., 2009; Thierfelder et al., 2013 |
| **Trap crops** | A crop planted to attract insect pests from another crop | Finch & Collier 2012; Phophi & Mafongoya, 2017 |
| **Natural enemies** | Control of insects by other living insects | Grzywacz et al., 2014 |
| **Plant extracts** | Using extracts from certain plant species to control pests | Grzywacz et al., 2014 |
| **Field sanitation** | Methods aimed at reducing or eradicating the host, sources and vectors of pests and diseases. | Mdluli et al., 2014 |
| **Intercropping** | Growing a crop among plants of a different kind | Bloem et al. 2009; Rusinamhodzi et al. 2012; Masvaya et al. 2017 |
| **Cover cropping** | A practice of growing a crop for soil protection and enrichment | Tsubo et al., 2003; Bloem et al., 2009; Murungu et al., 2011; Dube et al., 2012 |
| **Polycultures** | Simultaneous cultivation or exploitation of several crops | Hitayezu et al. 2016 |
| **Inclusion of legumes** | Growing of leguminous crops in space and time | Gwata & Mzezewa 2013 |
| **Varietal mixtures** | Several varieties of the same species, such as maize, sown mixed together | Mnkeni & Mutengwa 2014; van Niekerk & Wynberg 2017 |
| **Agroforestry** | A practice of growing trees in association or around crops or pastures | Paumgarten et al., 2005; Kelso and Jacobson 2011; Zerihun et al., 2014 |
| **Conservation agriculture (CA)** | A practice that comprises three components applied simultaneously in the field on: namely, planting basins, crop residue retention and crop associations through rotations | Sithole et al. 2016; Muzangwa et al. 2017 |
| **Gelesha** | A means of hoeing or the tilling of soil after a crop harvest | Denison & Wotshela 2009; Gandure, Walker, and Botha 2013 |
| **In field water harvesting** | A technique of maximising infiltration, reducing surface runoff and soil evaporation, and improving soil water availability to the crop | Mwenge Kahinda & Taigbenu 2011; Biazin et al. 2012 |
| **Rooftop water harvesting** | Water is collected from rooftops, courtyards and similar compacted surfaces and used for domestic purpose or garden crops | Mwenge Kahinda & Taigbenu 2011; Denison & Wotshela 2012 |
| **Application of animal manure/ compost** | Animal waste (predominantly urine and faeces) typically applied to soils as fertilizer for agricultural production | Mkhabela 2017; Materechera 2010 |
| **Land fallowing** | A practice of leaving the land bare piece with no crops on it for a season to let it recover | Shisanya & Mafongoya 2016 |
| **Mulching** | A process whereby a layer of grass or crop residues is applied to the soil surface | Botha et al. 2012; Maponya & Mpandeli 2013 |

#### 4.2.3.2 Focus group discussions to explore the uptake of the options

Fieldwork for this research was carried out from September 2017 to November 2017. During this time frame, the lead author spent three months collecting qualitative data through focus group discussions with agricultural extension officers and smallholder farmers from villages in the study locations. Focus group discussions were conducted in two steps. During the first phase, four agricultural extension officers in each local Municipality, namely Raymond Mhlaba and Thulamela were identified as key informants and meetings were organised with the key informants to supply missing information, eliminate bias and validate our preliminary literature-based findings. This helped present a general depiction of the validity and relevance of the 18 ecological intensification options identified in the two municipalities. Critical context information on government initiatives and efforts to identify, promote and implement ecological intensification options were gathered. The discussions with the agricultural extension officials clarified several relevant ecological intensification options. Moreover, the discussions were enabled and facilitated subsequent focus group discussions in the two study areas. Definitions were tailored for the farming communities focus group discussions (Table 4.1).

During the second phase, focus group discussions were conducted involving smallholder farmers in the study areas. In each study location, smallholder farmers who fitted in into typologies developed by Mkuhlani et al., (2018) and Rusere et al., (2019) were selected. The Mkuhlani et al., (2018) and Rusere et al., (2019) typologies of smallholder farm types in Vhembe District, Limpopo Province were cereal-and-livestock-based, horticulture-based and off-farm-income-based farms. Similarly, in Amathole District, in the Eastern Cape, mixed cereal-and-livestock, horticulture-based, social welfare-dependent, struggling subsistence and cooperative farms were the identified five smallholder farm types. The snowball sampling approach was used to identify 40 and 57 farmers in Raymond Mahlaba and Thulamela Municipalities, respectively, to participate in the focus group discussions. In Raymond Mahlaba Municipality, in the Eastern Cape, extension officers identified agroecology farmers and farmers who fitted into the horticulture-based and cereal and livestock-based farm typologies. Five focus group discussions took place in five villages, namely Amathola Basin with 7 farmers, in Mazotsheni with 5 farmers, in Tyali with 9 farmers, in Krwakrwa with 12 farmers and Adelaide with 7 farmers. In Adelaide and Tyali the farmers specialised in the production of horticultural crops, while in Krwakrwa farmers specialised in growing cereals and legumes with rearing of livestock. In Amathola Basin and Mzotsheni, the farmers receive training and technical support in agroecology from Oxfam South Africa. In Limpopo, Thulamela Municipality, three focus group discussions took place, in three villages namely, Saselamani, Mhinga and Ha Lambani with 27 cereal-and-livestock based, 13 horticulture-based and 17 off-farm-income-dependent farmers, respectively.

Agricultural extension officers served as translators from English to either Xhosa or Tshivenda languages in the Eastern Cape and Limpopo Provinces, respectively. Farmers were asked the following questions relating to their familiarity with and use of any of the above-mentioned ecological intensification options.

(i) Are you familiar with the following option? (Yes/No)
(ii) Do you use this option in your cropping activities? (Yes/No)
(iii) What role does the option play in your farming activities?

The responses to these questions were used to gain a general depiction of relevance, use and farmer knowledge of these ecological intensification options. Apart from this, the UTAUT conceptual framework outlined above, its key constructs of performance expectancy, effort expectancy, social influence, and enabling actors were used as themes to solicit information on aspects farmers consider before accepting and using a technology. Farmers were asked the question below to assess each of the above-mentioned ecological intensification options in terms of the four key themes of UTAUT framework.

The following questions were asked in relation to performance expectancy:

(i) Does the option perform a beneficial function in your cropping activities?
(ii) State the benefits derived from the use of the option in your cropping activities?

The following questions were asked in relation to ease of use:

(i) Is the option labour intensive?
(ii) Is there a cost associated with the option or is the initial cost high?

The following questions were asked in relation to social influence:

(i) How well does the option fit within the farmers environment?
(ii) How applicable is the option to all scales of farming?

The following questions were asked in relation to enabling actors:

(i) What can be done to improve acceptance and use of the option?

### 4.2.4 Data analysis

The information and data obtained from the various focus group discussions with smallholder farmers were coded and analysed. The transcripts were coded manually with text, phrases, and statements and these were subsequently linked and mapped against the four key constructs of the UTAUT framework namely performance, ease of use, social influence and enabling actors. Moderate editing of interview quotes and responses was done to enhance readability. This paper, therefore, reports on findings pertaining to the focus group discussions with smallholder farmers and it is not intended to make any statistical inferences for the study region. Its contribution is scope limited in this respect but transparent with respect to a detailed account of smallholder perspectives.

## 4.3 Results

First, we present focus group discussion results on smallholder farmers' familiarity and the use of these ecological intensification options in their farming activities. We then present the results on smallholder farmers' behavioural intention to accept and use ecological intensification options under the four key constructs of the UTAUT framework namely, performance, ease of use, social influence and enablers.

### 4.3.1 Familiarity and use of ecological intensification options by smallholder farmers

In both Municipalities, smallholder farmers were knowledgeable about the ecological intensification options presented in Table 4.2. The use of these ecological intensification options varied according to smallholder farmers production objectives. We present the results under three thematic areas namely pest suppression, soil management and intra-and-inter seasonal climate variability management.

#### 4.3.1.1 Pest suppression

Pests and diseases were not regarded as major challenges in the production of cereal crops and legumes. The cereal and livestock farmers revealed that pests and diseases only affected their small home gardens. Crop sanitation and land fallowing were practiced in arable fields. In contrast, horticulture-based farmers cited the incidences of pests and diseases as major obstacles to successful production. They noted the importance of crop diversification options in crop protection. Among the crop diversification options, polycultures, varietal mixtures intercropping and crop rotations, helped to control and break pest, diseases and weed cycles in horticultural cropping systems. Cereal and livestock, horticultural and agroecology farmers used plant extracts for example from onion and garlic to control crop insects' pests in their gardens on small scale. This was not a common practice in the other type of farming systems. It was observed that the use of trap crops and biological control through the use natural enemies for pest suppression was rare because most farmers were unaware of the methods. Nevertheless, agroecology farmers in Raymond Mahlaba Local Municipality indicated that they were aware of the potential of lady birds in the control of insect pests.

### 4.3.1.2 Soil management

Farmers across all the farm types highlighted low soil fertility and soil moisture deficits as major challenges. It was indicated that organic resources, such as animal manure, crop residues, and compost, were widely used to improve soil quality, fertility and water conservation. Legumes, although grown on a small scale were regarded crucial in cropping systems through crop diversification options, such as intercropping, cover cropping, rotations and polycultures. Their importance related to their ability to improve soil fertility through the fixation of nitrogen, which ultimately reduced the need for high exogenous application of inorganic fertilizers. In addition, crop residues from legume crops are used to feed livestock in cereal and livestock based farms especially during the dry season. The crop diversification options reduced runoff and increased infiltration resulting in enhanced water harvesting and conservation. Cereal-and-livestock and agroecology-based famers confirmed their exposure to conservation agriculture (CA) and in situ water harvesting techniques. In addition, they highlighted the potential benefits of improving the sustainability of soil through soil fertility and structure improvements. However, uptake was limited due to socio-economic and technical constraints such as shortage of labour and lack of experience. In the Eastern Cape, an indigenous practice of water harvesting, and soil conservation called *gelesha* was said to be common among farmers. it involved tilling the land immediately after harvest. This was done to ensure increased infiltration of rain, dew and frost, in addition to reducing runoff. Thus, the practice was crucial in increasing the availability of water for the next crop.

### 4.3.1.3 Management of intra-and-inter seasonal climate variability

Farmers were aware and wary of inter-and-intra seasonal droughts, which increased the risk of crop failure. Mitigation measures included investing variety and cultivar mixtures, cultivating multiple types of crops with the aim of increasing overall farm productivity and ensure that there would be harvest security within unpredictable climatic patterns. Polycultures, intercropping and crop rotations with vegetables and legumes, were crop diversification options utilised to help to reduce the risks of production failure in case of dry spells and droughts being experienced. These practices helped reduce the overall sensitivity of the farming systems to both intra-and-inter seasonal climate variations.

Roof top water harvesting techniques were also relied on. This made it possible to grow legumes and vegetables especially in their backyard home gardens with less use of external inputs and resources. As a result, they were direct benefits with respect to household diets. Agroforestry played a multi-seasonal long-term role in diversifying livelihoods. Consequently, reduced sensitivity and increased the adaptive capacity of farmers in household consumption. Surplus fruits were sold to generate income and reduce financial vulnerability to current and future climate risk. Non-fruit trees, such as Acacia species, are a source of supplementary forage fodder in livestock farming systems when pasture availability and quality declines during the dry season and drought years. Because of this critical role, tree species helped build the resilience of the farming systems to climate variability and change induced challenges.

### 4.3.2 Utilising the UTAUT framework in analysing ecological intensification options

The UTAUT theoretical framework suggests that acceptance and use of technology is explained by four key constructs namely, performance expectancy, effort expectancy social influence and enabling actors. We explored farmer perception on how ecological intensification options would apply under these four key constructs that influence technology acceptance and use. Table 4.3 is a summary of the farmer perceptions taking in to account the performance of the options, ease of use, compatibility with the socio-economic context and enabling conditions for acceptance and use of ecological intensification in smallholder farming systems.

#### 4.3.2.1 Performance expectancy

According to farmers' perceptions (Table 4.3), increased crop yields, soil fertility improvement, enhancement of soil water conservation, pest suppression and harvest security were the major performance indicators and major drivers for enabling acceptance and use of ecological intensification options. Farmer perceptions varied according to the role the option plays in their farming activities. For example, the use of organic animal manure, which was common practice across farmers, they expressed the following testimony in relation to increased crop yields and harvest security:

"Use of animal manure improves our crop yield. If you do not apply animal manure you will not get anything."

Other farmers expressed the following testimony in relation to soil fertility improvement:

"Use of animal manure increases soil organic matter hence increase microbial activity and ultimately improve soil fertility."

Other farmers expressed the following in relation to the enhancement of soil water conservation:

"If you apply animal manure it enables the soil to hold more water and enable the crops to survive during the long dry spell period."

Other options that were common where the use of crop rotations, polycultures and varietal mixtures. Farmers expressed the following comments in relation to pest suppression:

"If you keep on growing the same crop, pest and disease will build up, so you have to grow different crops or varieties to help minimise pest and diseases. I usually rotate maize with cowpeas or groundnuts"

#### 4.3.2.2 Effort expectancy

According to farmers perceptions (Table 4.3), labour intensity, availability of resources and production costs are the major indicators for effort expectancy and are the major drivers towards enabling acceptance and use of ecological intensification options. Farmer perception varied among options. For example, use of organic animal manure, farmers expressed mixed feeling in relation to its ease of use:

"It is easy to use animal manure because it is locally available and cheap, but it is difficult to get it to the field and also to have adequate amounts to support the whole field sufficiently."

Other options such as the use of conservation agriculture and in situ rainwater harvesting practices, farmers expressed the following testimony in relation to its labour demand:

"Conservation agriculture and in situ rainwater harvesting has been promoted but some of us are too old. It will be too much work for some of us."

Other options such as varietal mixtures, crop rotations and intercropping, some farmers expressed similar comments such as the following:

"It is very difficult to grow different crops on the same piece of land; they have different requirements and that becomes too much work for us. Also, it is very expensive to buy different types of seed of the same crop or for other crops. Seed is too expensive."

#### 4.3.2.3 Social influence

According to farmers' perceptions (Table 4.3), social referents such as compatibility with the socio-economic environment are the major indicators of social influence and are the major drivers towards enabling acceptance and use of ecological intensification options. Farmer perceptions varied according to option. For example, the following testimonies were made regarding conservation agriculture:

"Conservation agriculture is complex; we cannot retain crop residues to the soil. We have livestock to feed and we use those crop residues to feed our livestock during the dry season."

This means that farmers were faced with trade-offs for crop residue use, making acceptance and use of CA practices difficult in such an environment. Regarding crop rotations and polycultures, the following testimonies were made:

"We have to grow maize every season that is what we eat."

This means that farmers have their preferred crops, and this makes it difficult to introduce other crops or implement crop rotations.

Regarding agroforestry the following testimonies were made:

"We just grow fruit trees around our fields and our homes we learnt this for from our parents and grandparents. We do not know that trees and crops can be mixed together."

Regarding *gelesha* the following testimonies were made:

"That would be too much work. We also have other things to do after harvesting."

#### 4.3.2.4 Enabling actors

According to farmers' perceptions (Table 4.3), training, technical knowhow, resource availability, markets, and legislation are the major enablers and major drivers towards enabling acceptance and use of ecological intensification options. Farmer perceptions mainly focused on the above-mentioned enablers. For example, the following perceptions were made regarding polycultures and integrating legumes in their cropping systems:

"Where will we sell those other crops? We do not have markets for those other crops. Once markets and prices are good, we will grow those crops."

This means that farmers' lack access to markets or prices of the other non-preferred crops are not lucrative to them to enable them to accept and use such options.

Regarding other options such as intercropping, agroforestry, farmers expressed the need for skills, training and technical knowhow. The following comments were made:

"We do not even know which crops to intercrop and when to intercrop?"

Some farmers expressed knowledge of these options but have never seen the options being used practically. For example, the following comment was made by agroecology farmers in the Eastern Cape:

"We have heard that lady birds can be used to control pest, but we have never been exposed to such technologies"

This shows that farmers need skills training and technical know to enable acceptance and use of ecological intensification options.

Regarding options such as polycultures and varietal mixtures, some farmers expressed the following:

“We are not allowed to retain seed by law. This makes it difficult to grow different crops and varieties because seed is very expensive hence, we just only buy one variety for our main crop”.

*Table 4.2: Ecological intensification options exposed to and/or used by different farm types in smallholder agriculture in Limpopo and the Eastern Cape.*

| **Study area** | **Farm type** | **Pest suppression strategies** | **Soil management** | **Inter-and-intra seasonal climate variability management** |
|---|---|---|---|---|
| **Limpopo & Eastern Cape** | Cereal-&-livestock-based | - Field sanitation<br>- Land fallowing<br>- Plant extracts | - Intercropping<br>- Crop rotations<br>- Inclusion of legumes<br>- Application of animal manure<br>- Mulching<br>- In situ rainwater harvesting<br>- Gelesha<br>- Conservation agriculture (CA) | - Varietal mixtures<br>- Polycultures<br>- Agroforestry<br>- Roof top water harvesting |
| **Limpopo & Eastern Cape** | Horticulture-based | - Plant extracts<br>- Polycultures<br>- Varietal mixtures<br>- Intercropping<br>- Crop rotations<br>- Field sanitation | - Application of compost<br>- Application of manure<br>- Crop rotations<br>- Mulching<br>- In situ rainwater harvesting | - Varietal mixtures<br>- Polycultures<br>- Agroforestry<br>- Roof top water harvesting |
| **Eastern Cape** | Agroecology | - Field sanitation<br>- Intercropping<br>- Polycultures<br>- Crop rotations<br>- Plant extracts<br>- Natural enemies e.g lady bugs | - Application of compost<br>- Application of manure<br>- Cover cropping<br>- Intercropping<br>- Crop Rotations<br>- Inclusion of legumes<br>- Mulching<br>- Conservation agriculture (CA)<br>- Gelesha<br>- In situ rainwater harvesting | - Varietal mixtures<br>- Polycultures<br>- Agroforestry<br>- Roof top water harvesting |
| **Limpopo** | Off farm-income-based | - Field sanitation<br>- Land fallowing | - Application of manure<br>- Intercropping<br>- Inclusion of legumes | - Varietal mixtures<br>- Agroforestry<br>- Roof top water harvesting |

*Table 4.3: Key factors influencing potential adoption and or use of ecological intensification options in smallholder agriculture.*

| Option | Agronomic performance | Ease of use | Social influence | Enabling conditions |
|---|---|---|---|---|
| **Land fallowing** | - Breaks pest and disease cycles<br>- Improves soil fertility | - No costs | - Resource under utilisation<br>- Land underutilisation<br>- Simple | - Land availability |
| **Conservation agriculture (CA)** | - Increases crop yields<br>- Ensures harvest security<br>- Improves soil fertility<br>- Promotes soil and water conservation | - labour intensive | - Complex<br>- Trade-off for mulch use<br>- Lack of experience | - Training<br>- Technical knowhow and support |
| **In situ rainwater harvesting** | - Increase crop yields<br>- Ensures harvest security<br>- Promotes soil and water conservation | - High investment costs<br>- Labour intensive | - Complex<br>- Trade-off for mulch use<br>- Lack of experience | - Training<br>- Technical know and support |
| **Gelesha** | - Promotes soil and water conservation | - Labour intensive | - Competition with off season activities | - Training<br>- Technical support |
| **Roof top water harvesting** | - Promotes soil and water conservation | - Low investment costs | - Simple | |
| **Application of organic manures** | - Increases crop yields<br>- Ensures harvest security<br>- Improves soil fertility<br>- Promotes soil and water conservation | - Resources locally available<br>- Low investment cost<br>- Labour intensive<br>- Insufficient quantities<br>- Handling and transportation challenges | - Simple | - Resource availability<br>- Technical knowhow and support |
| **Mulching** | - Promotes soil and water conservation<br>- Improves soil fertility | - Resources locally available<br>- Labour intensive<br>- Insufficient quantities<br>- handling and transportation challenges | - Simple<br>- Trade-off for mulch use | - Resource availability<br>- Training<br>- Technical knowhow and support |
| **Crop rotation** | - Increases crop yields<br>- Ensures harvest security<br>- Improves soil fertility | - Labour intensive<br>- High germplasm cost and limited access | - Complex<br>- Food diversity | - Land availability<br>- Markets<br>- Resource availability |

| | | | | |
|---|---|---|---|---|
| | - Promotes soil and water conservation<br>- Breaks pest and diseases life cycles | | - Crop preference trade-offs<br>- Competition for resources<br>- Lack of experience<br>- Land limitation | - Technical knowhow and support |
| **Intercropping** | - Increases crop yields<br>- Ensures harvest security<br>- Improves soil fertility<br>- Promote soil and water conservation | - Labour intensive | - Complex<br>- Food diversity<br>- Crop preference trade offs<br>- Competition for resource<br>- Lack of experience | - Markets<br>- Technical knowhow and support<br>- Resource availability |
| **Cover cropping** | - Increases crop yields<br>- Improves soil fertility<br>- Promote soil and water conservation | - Labour intensive<br>- Limited access to germplasm | - Food diversity<br>- Crop preference trade offs<br>- Competition for resources<br>- Lack of experience | - Markets<br>- Technical knowhow and support<br>- Resource availability |
| **Polycultures & varietal mixtures** | - Increases crop yields<br>- Ensures harvest security<br>- Breaks pest and diseases life cycles<br>- Improves soil fertility<br>- Promotes soil and water conservation | - Labour intensive<br>- Limited access to germplasm<br>- Land limitation | - High investment cost<br>- Lack of experience<br>- Food diversity<br>- Competition for resources<br>- Crop preference trade offs | - Markets<br>- Technical knowhow and support<br>- Resource availability<br>- Legislation |
| **Agroforestry** | - Ensures harvest security | - Limited access to germplasm | - Complex<br>- Food diversity<br>- Lack of experience | - Technical knowhow and support<br>- Training<br>- Resource availability |
| **Plant extracts, natural enemies and trap crops** | - Breaks pest and diseases life cycles<br>- Ensures harvest security | - Cheap<br>- Resources locally available | - Complex<br>- Lack of experience | - Technical knowhow and support<br>- Training |
| **Field sanitation** | - Breaks pest and diseases like cycles<br>- Ensures harvest security | - Labour intensive<br>- Cheap | - Complex<br>- Lack of experience | - Technical knowhow |

## 4.4. Discussion

### 4.4.1 Relevance of ecological intensification options in smallholder farming systems in South Africa

Ecological intensification is a pathway designed to improve productivity, increase climate variability and change adaptive capacity and reduce vulnerability in these smallholder farming communities. Ecological intensification advocates for strategies that are rooted in crop diversity. Diversification of crops lowers the chances of total crop failure and increases resilience by ensuring harvest security (Mccord et al., 2015). For example, while most smallholders prefer to grow cereal crops, such as maize and sorghum. These crops tend to have long cropping cycles, making them more susceptible and vulnerable to climate variability and change impacts, thus have a high chanceof crop failure. On contrast, crops such as legumes and leafy vegetables have short production cycles, are fast growing, require small pieces of land, and thus, can be considered less susceptible and vulnerable to climate variability and change impacts. Using locally relevant and indigenous knowledge is an additional advantage, allowing farmers to favour varieties that suit their environmental conditions. This ultimately improves overall farm productivity, yield stability and resilience to changing climatic patterns.

Nowadays, the issue of environmental sustainability is clearly embedded within the discourse of agricultural intensification. In situations where environmental sustainability and agricultural intensification seem incompatible and contradictory (Garnett et al., 2013), ecological intensification could provide a bargain in terms of both productivity and environmental sustainability (Garbach et al., 2017). Soil fertility is regarded as one of the dominant constraints in South African smallholder systems (Materechera, 2010). Farm level management decisions, such as continuous mono-cropping on the same plot, result in nutrient mining, soil erosion and contribute to a decline in soil fertility, exacerbate land degradation and shrinkage of the natural resource base. In addition, most smallholder farmers lack knowledge on pesticide use and disposal, leading to misuse and improper disposal of agricultural pesticides with serious environmental consequences (Njeru, 2013; Sheahan & Barrett, 2017). Any form of degradation tends to reduce their agricultural productivity and income, which often amplifies the cycle of poverty and environmental deterioration. The implementing of ecological intensification options enhances pest suppression ecosystem services through crop diversification options, such as polycultures including intercropping and rotations (Gurr et al., 2016). It helps reduce the need for pesticides thus reducing environmental contamination, degradation and crop losses. Through crop diversification-based options, soil structure and soil biological biodiversity are inherently improved, thus enhancing nutrient recycling (Tiemann et al., 2015). Ecological intensification, hence, has the potential to eradicate inequality, poverty and environmental deterioration.

Options for ecological intensification suit and fit well within the contrasting biophysical and socio-economic conditions of the heterogeneous smallholder farms. The paradigm of ecological intensification is a low-cost intensification pathway, it requires few external inputs, and makes better use of locally available resources, hence, it is particularly suited to the vulnerable and resource constrained South African smallholder farmers associated with poverty. Furthermore, its ability to incorporate locally relevant and indigenous knowledge can improve social capacity, increase the quality and quantity of natural resources gradually within farming landscapes and communities. Ecological intensification maybe a relevant option for intensification, thus it may transform smallholder farming landscapes and systems to enhance agricultural production and contribute to sustainable development in the poorest rural areas of South Africa.

### 4.4.2 Smallholder farmers' acceptance and use of ecological intensification in South Africa

Implementing ecological intensification is a knowledge intensive and complex process (Garibaldi et al., 2016). According to our findings, working with farmers could increase acceptance and use of ecological intensification options in their farming systems because uptake is influenced factors that range from personal, social, cultural to economic factors. Mutual learning between farmers and researchers could overcome these complexities (Landis, 2016). Smallholder farmers face a lot of trade-offs in their farming activities. Trade-offs largely occur between enhancing agricultural production or minimizing environmental damage and trade-offs for farm resources use to either enhance productivity or to cater for other livelihood options. However, discussions on trade-offs at farm level in smallholder agricultural systems are still largely missing in the ongoing discussions of agricultural intensification of smallholder agriculture systems. Such information on trade-offs is vital as it influences the acceptance and use of agricultural innovations and technologies for agricultural intensification (Giller et al. 2011).

We used a four key constructs framework to assess behavioural intention to accept and use a technology and highlight issues that must be addressed if ecological intensification is to be accepted and successfully implemented in smallholder farming systems in South Africa. The actual implementation of our framework leads to a better understanding of the situation to be transformed for both researchers and farmers. We explicitly make the effort to go beyond performance to consider other aspects, such as effort, social influence and enabling actors needed, which play an indiscernible role in influencing the acceptance and use of different technologies.

#### 4.4.2.1 Performance expectancy

The performance of an agricultural technology is a critical determinant of acceptance and use in farming systems. When assessing cropping systems performance or agricultural technologies, attention is placed on direct or indirect outcomes. Typically, indicators such as productivity (yield), resource use efficiency or profitability, which are direct outcomes, to smallholder households, are usually employed in the evaluation process. In addition, other indirect outcomes, such as improved soil fertility, pest suppression among others are also used to assess the performance of cropping systems. Scientists and researchers tend to focus on crop yield as the main metric for assessing performance agricultural technologies. While it gives a numerical proxy for cropping system potential, it often lacks accounting for household constraints and limitations. For instance, our results showed that, for many farmers, ecological intensification options were highly useful and impacted positively on yield and resource use efficiency of inputs. Yet, this is not enough to ensure acceptance, as it does not necessarily match with priorities of farmers, who may value food quantity more than productivity, or production stability over time more than yield maximization.

Most agricultural intensification studies hypothesize livelihoods of smallholder farmers will improve as yields increases (Trimmer et al., 2017; Liao & Brown, 2018). Yet, meeting home consumption requirements is a top priority for most smallholder farmers across much of Africa, often putting consistency ahead of productivity. Even if those are not necessarily conflicting, they are not clearly aligning with the original hypothesis that one implies the other. The yield stabilising effect brought about by ecological intensification options through nutrient recycling, pest suppression, and soil and water conservation ecosystem services, makes the cropping systems more resilient, thus enhancing food security. For example, our results show that crop diversification options lead to consistent and reliable harvest, thus increasing their acceptance and use in smallholder farming systems.

#### 4.4.2.2 Effort expectancy

The decision to use a technology largely depends and lies on the farmers' strategies, which translate into a consistent set of farm management practices aimed at reaching a particular goal. These strategies are largely influenced by financial, labour and input resources. For example, a farmer may choose not to accept or use a technology that enhances productivity due to its increased labour demand. The ease of use of ecological intensification options is consequently an important factor, which widely differs among farmers and options. Some ecological intensification options such as conservation agriculture and in situ rainwater harvesting, which are promoted in rural South Africa, were noted to be complex, in addition to being labour intensive. Many farms are headed by elderly farmers with limited physical capacity and access to manual labour; this complexity makes those options less likely to be accepted and used. Early engagement with smallholder farmers during the design process allows interrogation and definition of those contrasting priorities and proceeding with better tailored assessments. This could enhance the acceptance and use of ecological intensification options by identifying and addressing adoption and out-scaling barriers. For example, the creation of farmer field schools to facilitate the exchange of relatable experiences and solutions, or as agricultural innovation centres, gives smallholder farmers a platform to explore, learn, experience and exchange knowledge with other farmers, researchers and stakeholders.

#### 4.4.2.3 Social influence on the use of ecological intensification options

Values, degree of trust, norms and attitudes are social aspects that do influence technology acceptance and use, beyond productivity and effort of specific options. For instance, maize is a commonly grown crop and the main staple crop in the study areas despite repeated low yields and low returns. Maize dominance in these areas is enormous relative to its low potential, and largely motivated by food preference and strong social support. This and other social norms present a challenge for smallholders to accept and use ecological intensification options that promote crop diversification. In the maize case, it challenges the promotion of crop diversification options, such as crop rotations, intercropping or polycultures, which offer more competition for resources to maize to realise yield, over limited land availability.

The heterogeneous nature of smallholder agricultural systems also results from the diverse social systems. These translate into different trade-offs, likely to influence technology acceptance and use differently through farm types. In our study areas, livestock is highly valued, especially cattle, because of the major roles it plays at farm level. Farmers keep livestock even under scarcity of grazing land and feed, adapting feed practices to what is locally and seasonally available. Crop residues, for instance, are normally harvested, removed from the fields and stored in heaps so that they provide supplementary livestock feed particularly during the dry season when pasture availability and quality are limited. In the communities surveyed, competing uses for crop residue for soil cover and use as a supplementary livestock feed exist. The limited production of crop residue, subject to competing demands, emerged as a key issue and constraint for acceptance and use of some ecological intensification options. Conservation agriculture (CA) and in situ rainwater harvesting options, for instance, emphasize the retention crop residues on the soil surface in smallholder farming systems, making no clear provision for supplementary feed. It is debatable that smallholder farmers can concurrently produce sufficient crop residues for retention in cropping fields and for supplementary feed for sustained livestock production. This shows that technologies must be carefully tested on how varying social factors impact their acceptance and use given the socio-economic context of farmers.

#### 4.4.2.4 Enabling conditions for acceptance and use of ecological intensification options

Several routes can be pursued to enable ecological intensification in smallholder agriculture. One such route is increased awareness and access to information because improved knowledge on the use and potential benefits of ecological intensification options allows farmers to properly assess the impact of these options on their farming systems. Most farmers acknowledged being aware of the above ecological intensification options but lacked knowledge and skills needed for their integration and implementation. These observations concur with other studies which asserted that smallholder farmers in South Africa lacked knowledge and skills on CA and other climate smart agricultural practices (Muzangwa et al. 2017; Senyolo et al. 2017). Awareness, knowledge and training are particularly critical in crop diversification options, such as crop rotations, intercropping, trap crops and polycultures, and in our case, farmers were unaware of ideal cultivars/varieties or crops to use for such options. Facilitating tailored education programs and initiatives and providing adequate access to locally relevant technical and extension support services, is a locally relevant direction to improve smallholder farmers' access to locally relevant information and knowledge, and consequently improve the acceptance and use of ecological intensification options.

We found that increased affordability and availability of farm input resources could enable a significant increase of the acceptance and use of ecological intensification options and new agricultural technologies. Studies on crop diversification options by Waha et al. (2018) and Hitayezu et al., (2016) noted that resource-poor smallholder farming households appear willing to grow different crops, but high cost needed for inputs such as seed and other production related costs, strongly de-incentivise farmers. Although studies by Zerihun et al. (2014) asserted that agroforestry is common in South African smallholder farming systems mainly through fruit tree production around their homesteads and cropping fields. However, lack of agroforestry germplasm and propagation material has been recognised as a constraint to the wider uptake of agroforestry for enhancing soil fertility and soil and water conservation in such smallholder systems (Mbow et al., 2014; Meijer et al., 2015). In our findings, smallholder farmers access resources such as seed (germplasm) through savings and exchange. Buying locally approved varieties is a common constraint due to limited financial and technical know-how on suitable varieties. In the Eastern Cape, for example, farmers revealed that issues relating to laws prohibiting the retaining of seed by farmers are a major obstacle in implementing crop diversification options. Consequently, the potential of crop diversification in smallholder farming communities is limited due to legislation, limited access, availability and affordability of germplasm of other non-preferred crops in smallholder farming communities. Policies and institutions need to be put in place to enable better access to, and affordability of, farm input resources in smallholder farming communities.

Institutional accessibility, for instance, the proximity to both input and output markets also influences technology acceptance and use. When input and output markets are far from farms, farmers are unable to access the required crop production inputs or to sell their products. It is further articulated by Mariano et al. (2012) and Tessema et al. (2013) that, despite the positive attributes of new and promising technologies and practices and considerable energies put into enticing farmers to adopt them, adoption of promising technologies is also largely influenced by institutional factors, such as input and output markets. For example, the promotion of leguminous crops, which increase the fertility of nutrient deficient soils, remains limited due to limited access and availability of leguminous markets. Therefore, the rapid transformation of smallholder agriculture towards ecological intensification is highly dependent on the availability of markets of the other non-preferred crops.

### 4.4.3 Transition towards acceptance and use of ecological intensification in smallholder farming systems

Through the concurrent assessment of the four key constructs of the UTAUT framework, we were able to gain a depiction of smallholder farming communities' priorities and trade-offs towards the acceptance and use of ecological intensification. Most farmers were familiar with, and appreciated, ecological intensification options, for instance in terms of soil fertility improvement, pests and diseases suppression, yield improvement and stability. In our study areas, smallholder farmers currently benefit or could benefit from ecological intensification options, making ecological intensification an attractive, promising, feasible and viable option for intensification in smallholder farming communities.

Although farmers recognised the value of ecological intensification options and associated them with yield and productivity gains, other factors they consider before accepting and using a technology are hindering their acceptance and use. Factors such as land constraints, labour, lack of technical knowhow, lack of technical or extension support, lack of markets, socio-economic issues, resources, and farmers consequent trade-offs need to be explored beyond mere productivity benefits. Smallholder farmers may not invest in options that are costly, labour intensive or which conflict with other farmer's goals. Unless these concurrent goals and constraints are also addressed, the feasibility and viability of ecological intensification will be questionable, making its acceptance and use difficult. To enable ecological intensification acceptance and use, best-fit management practices must be tailored according to the socio-economic aspects of the communities, farming systems and their environmental context. In addition, there is a need for these efforts to be supported by institutions, for instance through increasing access to market opportunities for alternative crops resulting from diversification.

Smallholder farming communities are heterogeneous in terms of resource endowments, production objectives and their biophysical environments, adding to the inherent complexity in enabling ecological intensification acceptance and use. Ecological intensification options which may be beneficial for one farmer may not always be beneficial to another. The heterogeneous nature of smallholder farming communities translates into different production objectives, synergies and trade-offs. These must be carefully considered to create conducive conditions for acceptance and effective use of ecological intensification in smallholder farming communities.

## 4.5 Conclusions

This study provides further evidence on farmer perceptions that ecological intensification practices and options are relevant to smallholder farming systems. They are instrumental in improving the sustainability of soil through enhancing soil fertility, promoting both soil and soil water conservation. Apart from improving soil health ecological intensification options improve productivity and impart stability of smallholder agroecosystems. In our case, the UTAUT framework demonstrated the importance of assessing promising agricultural technologies in a holistic manner. Overall, the analysis clarified and revealed trade-offs and synergies related to the diverse farm types, farmer objectives and the smallholder farming community more broadly. Working towards best-fit ecological intensification options requires participatory on-farm experimentation coupled with coordinated extension support. The latter should be carried out such that the smallholder farming communities are actively involved. Such an approach helps raise awareness and enables farmers to acquire agronomic skills in variety selection, planting time, cropping density and cropping patterns. Moreover, the involvement of farmers would provide opportunities for them to tailor information transfer better than is the case at present. Ecologically inspired approaches rely on biodiversity to enhance resilience. Therefore, the observation of biodiversity patterns, through mapping their effectiveness, would promote the emergence of relevant agroecosystem services. Given the importance of crop diversity in ecological intensification, various crop cultivars, including native species and old landraces known among smallholder farmers should be explicitly considered, taking into account factors of acceptance and use beyond productivity only.

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# CHAPTER 5

# Integrating a crop model with a greenhouse gas calculator to identify low carbon agricultural intensification options for smallholder farmers in rural South Africa

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# Abstract

Sustainable and ecological intensification are gaining momentum as new approaches to intensify smallholder agricultural systems in sub Saharan Africa. However, few studies have examined the sustainability of these intensification models in reducing the impacts of agriculture on the climate system. While several models and methods have been developed to estimate crop yields and greenhouse gas (GHG) emissions from cropping systems, there is lack of robust integrated models that enable estimation of crop yields and GHG emissions concurrently. This study develops a biophysical modelling framework encompassing a farm typology, a crop model and a farm focused calculator to assess productivity and GHG emissions of crop management practices to develop an approach that supports mitigation from the different farm types. An expert-based farm typology describing the diversity of maize based cropping systems was developed for two rural districts in South Africa. A cropping system model (Decision Support System for Agrotechnology Transfer; DSSAT) is combined with a farm level greenhouse calculator (Cool Farm Tool; CFT) to assess the crop yields and GHG emissions from the maize-based cropping systems from the different farm types developed from the expert-based farm typology. Using this modelling framework, the study then developed cropping system scenarios based on the concept of conservation agriculture (CA) to identify and design cropping systems that deliver ecological intensification, in which productivity and ecosystem services that support mitigation are simultaneously enhanced at farm level. The models indicated that farms were experiencing low crop yields ranging from 0.2 to 1.1 tha$^{-1}$ and were also net sources of GHG with emission ranging from 350 to 1538 kgCO$_2$eha$^{-1}$ indicating cropping system inefficiency across all farm types. Integration of CA-based practices independently and in combination into maize based cropping systems showed significant potential in improving crop yields and lowering GHG emissions across all farm types. The productivity and mitigation potential were highest with the full CA package with simulated crop yields which ranged from 1.6 to 3.9 tha$^{-1}$ while the mitigation potential ranged from -861 to -1923 kgCO$_2$eha$^{-1}$ across the farm types. Thus, CA practices in combination demonstrated to be more efficient and able to deliver ecological intensification, in which productivity is improved and ecosystem services such as climate change regulation simultaneously increased to enhance environmental sustainability. This study, concludes that the approach of combining integrated modelling with a detailed farm typology can identify agricultural intensification options that maintain or increase crop yields while reducing GHG emissions at the farm level. This can guide policy simulations and scenario analysis; especially where agricultural development programs involve preference of one sustainability dimension over another.

Keywords: conservation agriculture, crop yields, greenhouse gas emissions, smallholder agriculture, ecological intensification

## 5.1 Introduction

Issues of agricultural intensification and environmental sustainability have become highly topical because of food insecurity and climate change impacts in sub Saharan Africa (SSA) (Rockstrom et al., 2017). Sustainable and ecological intensification have been advocated as viable pathways to improve and increase food production because they have the potential to increase productivity and ensure environmental sustainability, especially in smallholder farming systems in SSA (Pretty et al., 2011). At the same time, there is growing agreement from the scientific and development community that agricultural intensification in SSA should evolve in parallel with environmental sustainability (Soussana, 2014), which must involve reducing agricultural related greenhouse gas emissions (GHG) (Hunter et al., 2017). Currently, Africa's GHG emissions, particularly from the agriculture sector are among the fastest growing emissions in the world (Tongwane & Moeletsi 2018). It is estimated that smallholder agricultural systems, including livestock production, are responsible for significantly contributing up to 32 % of the agricultural sector emissions in SSA (Descheemaeker et al., 2016). Smallholder farmers are expected to intensify agricultural systems to close the wide yield gaps and meet the growing food demand and food security challenges of the rapidly growing SSA population (Holden, 2018). Bennetzen et al., (2016) argue that agricultural intensification and GHG emissions are closely connected. While current GHG emissions in smallholder farming systems are significantly high, reversing or simply slowing them down will require agricultural intensification models that are efficient (Bajželj et al., 2014). However, it remains unclear how sustainable and ecological intensification may affect whole-farm GHGs balances in SSA (Jin et al., 2017).

Conservation agriculture (CA) is being promoted and advocated as a panacea and pathway to deliver both sustainable and ecological intensification (Giller et al., 2015), and mitigation in smallholder cropping systems (Pretty & Bharucha 2014). However, considerable debate still exists in literature on whether CA is the best approach to intensify smallholder farming systems, and on whether CA simultaneously addresses yield gaps, climate change adaptation and mitigation challenges in cropping systems of smallholder farmers in SSA (Giller et al., 2015). CA hinges and is based on integrating three main agroecological principles which are: (i) reduced soil disturbance through minimum or no tillage, (ii) crop associations through diversification of crops (often with legumes) in space and time, and (iii) retaining and leaving at least 30% of crop residues to maintain a semi-permanent or permanent soil cover (Stevenson et al., 2014). Smallholder farmers rarely implement the full CA package and question the suitability of CA in the sub Saharan African smallholder context (Thierfelder et al., 2018). Moreover, studies on the contribution of the different CA components to reducing GHG emissions is still largely lacking in SSA. Most have focused on closing yield gaps and adapting to climate change, rather than on mitigation potential and environmental degradation. This may be due to the limited information and/ or lack of records on the GHG inventories of smallholder cropping systems (Suckall et al., 2014).

Herrero et al., (2008) highlight that data quantifying existing GHG emissions from smallholder crop and livestock production systems is limited and if available, it is only for a few crops, livestock and agroecosystems. Yet GHG emissions must be considered in farming system design if smallholders are to achieve goals of improving productivity and environmental sustainability (Bryan et al., 2013). Although studies on GHG emission focus on the GHG emission reduction potential of alternative farming practices, most do not concurrently pay sufficient attention to yield and livelihood impacts for smallholders (Rosenstock et al., 2013). Quantification of only GHGs is not helpful from a development perspective, if yield benefits of those options are ignored, because crop productivity and yield are connectedly linked to household food security of smallholder farmers in SSA (Linquist et al., 2012). Decisions on crop management are made at farm level, therefore any potential mitigation benefits should also be accounted at the farm level (Adewale et al., 2019). It is therefore vital and important to develop integrated modelling approaches that can quantify the impacts of crop management practices on both crop yields and GHG emissions simultaneously when designing sustainable cropping systems for heterogeneous smallholder farming systems.

Simulation models are useful tools to explore those aspects concurrently. However, they have not been used significantly in smallholder agricultural systems to explore the performance of relevant agricultural technologies. To date, simulation modelling has not received much attention in complex and heterogenous smallholder farming systems in SSA despite the useful explorative role they can play. Precise and accurate quantification of smallholder agricultural yields is challenged by factors such as highly heterogeneous crop performance within plots, highly heterogeneous cropping landscapes or lack of formal record-keeping at farm level (Jin et al., 2017). Although several methodologies and simulation models have been developed to quantify crop yields, they each come with their associated advantages and disadvantages (Sapkota et al., 2016). Biophysical and process based crop simulation models have been extensively used to estimate crop yields (Holzworth et al., 2015), analyse the impact of climate change on future crop yields (Rötter et al. , 2018), analyse the impact of land-use change in smallholder farming systems in SSA (Grassini et al., 2015). Crop models can also be used for strategic, tactical or operational decision support in on farm crop management (Webber et al., 2014). However, crop models are unable to simulate GHG emission consequences of different cropping systems.

GHGs calculators use simple accounting approaches based on a mix of emission factors and empirical models to calculate GHG emissions with minimal input data (Hillier et al., 2011). GHG calculators can be used by non-experts to estimate and quantify GHG emissions from agriculture related activities. Furthermore, GHG calculators are also inexpensive and rapid when compared to other methods of quantifying GHG emissions such as *in-situ* measurements (Sykes et al., 2017). These GHG calculators have been developed to quantify and estimate GHG emissions of cropping systems (Peter et al., 2017). However, most GHG calculators often fail to consider any changes in agricultural management practices to estimate crop yield improvements (Colomb et al., 2013). This is because the yield estimation of a particular cropping system may not properly reflect the yield estimate for a new cropping system. As a result, the level of uncertainty associated with these GHG calculators is high such that they may fail to properly expose or reveal mitigation options along the agricultural production chain (Richards et al., 2016).

Increased use of yield and GHG estimation tools in Africa would significantly increase our knowledge and figure out impacts of alternative interventions, and help target those which improve productivity and environmental sustainability, using much less resources and time than field experimentation (Masikati et al., 2017). In this study, we demonstrate how a crop model, Decision Support System for Agrotechnology Transfer (DSSAT v4.6) and a farm focused greenhouse calculator (The Cool Farm Tool) are combined to explore and assess the productivity (yield) and sustainability (GHG mitigation) of farm typology maize based cropping systems from different farm types in smallholder agricultural systems and communities in rural South Africa. Using this modelling framework, we use the concept of CA as a guide to remodelling of cropping systems and assess the potential of redesigned cropping systems to improve crop productivity, contribute to increased agricultural production with low GHG emissions, environmental sustainability and ultimately deliver ecological intensification in smallholder cropping systems.

## 5.2 Materials and methods

### 5.2.1 Study area

This study was carried out in Vhembe District, Limpopo and Amathole District, in the Eastern Cape, South Africa. These two districts are mainly rural, and mostly made up of smallholder farms, who practice rainfed agriculture on small pieces of land, usually 0.5 to 2 ha. Maize, legumes and vegetables are the main crops grown in these study areas. Depending on their level of resource endowment, farmers own cattle, donkeys, goats, sheep, pigs and poultry. In Vhembe district, the study was conducted in Ha Lambani, a semi-arid area with a tropical climate. The area receives most of its rainfall between October and January, and is frequently affected by dry spells, often escalating into a severe drought (Ubisi et al., 2017). In Amathole District, the study was conducted in Raymond Mhlaba Local Municipality, a semi-arid area with a temperate climate. The area experiences a bi-modal rainfall pattern. Thus, it receives both summer and winter rainfall, with an average annual rainfall not exceeding 600 mm (Chari et al., 2018).

### 5.2.2 Farm typologies and cropping systems attributes

The farm typologies and related cropping system attributes used in this study come from Rusere et al., (2019) and Mkuhlani et al., (2019), and are based on a survey of representative smallholder farms, in consultation with local experts in the two study regions. Rusere et al., (2019) and Mkuhlani et al., (2019) identified three farm types in Ha Lambani, namely cereal and livestock-based farmers, horticulture-based farmers and off-farm income-dependent farmers. In Amathole five farm types were identified namely, cereal and livestock-based, horticulture-based, cooperative farms, social welfare and struggling subsistence farms. In this study, the social welfare and struggling subsistence farms from Amathole were merged into one farm type. We collated and analysed the survey data and characterised cropping systems for each farm type in each study location. We tailored and validated the compatibility and relevance of the cropping systems to the farm types and study locations defined in Tables 1 and 2 through focus group discussions with local agricultural experts (mainly agricultural extension officers).

*Table 5.1: Description of the cropping system patterns and agronomic practices in different farm types in Ha Lambani, Limpopo, South Africa*

| Farm type | Crop | Power source | Tillage | Fertilizer type and application rate | Crop residue management |
|---|---|---|---|---|---|
| **Cereal and livestock (CL)** | Maize | Draught power | Ox drawn ploughing | Cattle manure @ 5000 kgha$^{-1.}$<br>Compound fertiliser 2:3:2@ 50 kgha$^{-1}$<br>Ammonium Nitrate (AN) @ 50 kgha$^{-1}$ | Removed to feed livestock |
| **Horticulture (Hort)** | Maize | Tractor | Ploughing and disking | Cattle manure @ 5000 kgha$^{-1.}$<br>Compound fertiliser 2:3:2 @ 250 kgha$^{-1}$<br>Ammonium Nitrate (AN) @ 150 kgha$^{-1}$ | Ploughed in |
| **Off farm income (OFI)** | Maize | Draught power | Ox drawn ploughing | Cattle manure@ 2000 kgha$^{-1}$ | Left in the field |

*Table 5.2: Description of the cropping system patterns and agronomic practices in different farm types in Amathole, in the Eastern Cape, South Africa*

| Farm type | Crop | Power source | Tillage | Fertilizer type and application rate | Crop residue management |
|---|---|---|---|---|---|
| **Cereal and livestock (CL)** | Maize | Draught power | Ox drawn ploughing | Cattle manure @ 5000 kgha$^{-1.}$<br>Compound fertiliser 2:3:2@ 50 kgha$^{-1}$<br>Ammonium Nitrate (AN) @ 50 kgha$^{-1}$ | Removed to feed livestock |
| **Horticulture (Hort)** | Maize | Tractor | Ploughing and disking | Cattle manure @ 5000 kgha$^{-1.}$<br>Compound fertiliser 2:3:2 @ 250 kgha$^{-1}$<br>Ammonium Nitrate (AN) @ 100 kgha$^{-1}$ | Ploughed in |
| **Cooperative (CP)** | Maize | Tractor | Ploughing and disking | Cattle manure@ 2000 kgha$^{-1}$<br>Compound fertiliser 2:3:2 @ 150 kgha$^{-1}$<br>Ammonium Nitrate (AN) @ 50 kgha$^{-1}$ | Left untreated in heaps and pits to make compost |
| **Social welfare dependent and struggling subsistence (SWSS)** | Maize |  | Hoeing | Cattle manure@ 2000 kgha$^{-1}$<br>Compost @ 250 kgha$^{-1}$ | Left untreated in heaps and pits to make compost |

### 5.2.3 Model descriptions

Models descriptions and their applications in this study are given below.

#### 5.2.3.1 DSSAT Model

The Decision Support System for Agrotechnology Transfer (DSSAT v4.6) is a comprehensive framework of more than 28 biophysical models (Jones et al., 2003; Hoogenboom et al., 2017). DSSAT simulates indicators such as crop growth, yield and water demand in response to the timely interactions of physiological, climatic, soil, and management conditions. DSSAT has successfully been used in SSA for crop yield simulations under different management strategies, soil and climate scenarios, to optimise resource use, for crop yield risk analysis, at a variety of locations with high validity (Zinyengere et al., 2015). DSSAT extensive use in SSA as a tool to compare different crop management practices under diverse soil and climate conditions, its experimented capacity to integrate with other models in the past (Anderson et al., 2018), and previous performance of the DSSAT in simulating maize yield under CA (Corbeels et al., 2016), makes it suitable for our application.

#### 5.2.3.2 Cool Farm Tool

The Cool Farm Tool (CFT) (Hillier et al., 2011) is a model that calculates agriculture related GHG emissions. The CFT is an integration of several globally determined empirical GHG quantification models in one tool. In this tool, GHG emissions are estimated and quantified using empirical models and emission factors which consider differences between production systems, regions and climates (Aryal et al., 2015). The model can recognise context specific factors such as soil characteristics, climate, production inputs and other management practices that influence GHG emissions at the farm level. The tool has been ranked highly in the public domain and has a strong farm-level focus (Whittaker et al., 2013). The CFT has been used in several studies such as model comparisons (Colomb et al., 2013), crop life cycle assessments (Aryal et al., 2015) as well as to explore various strategies for mitigation globally (Hillier et al., 2012). The CFT allows us to assess the performance of cropping systems at the farm level both in terms of land-use efficiency and efficiency per unit of product. In addition, the CFT can be used to inform current agricultural practices potential to mitigate climate change. Its detailed crop sub module, which can account for land use changes, fertiliser applications and management changes such as tillage or cover cropping, fits the study ambition of integration with a management sensitive crop model.

### 5.2.4 Modelling framework

Our central hypothesis was that coupling the CFT with crop yield data from DSSAT can help identify and package together individually proven ecological intensification farming practices which can simultaneously support both productivity and environmental sustainability in smallholder cropping systems. Two stand-alone models, a crop model and a greenhouse gas calculator, were ran separately but in coordination, as the outputs of one of the models were used as input for the other model (Figure 5.1). The crop model was calibrated to represent the agroecological regions of Vhembe and Amathole District in Limpopo and the Eastern Cape respectively. We used maize, a common crop in all farm types to illustrate the utility of the modelling framework. Maize crop yields from the different farm types are simulated in response to farm type management practices with the crop model and input into the greenhouse gas calculator to estimate GHG emissions per unit area and per unit crop yield in response to those simulated farm type management practices. We identified emissions range for management practices of each farm type and explored the impact of agroecological practices of CA individually and in combination intensification options for both crop yield improvement and carbon sequestration at the farm scale. This allowed us to identify management practices that enhance productivity and environmental sustainability for ecological intensification options of smallholder cropping systems.

### 5.2.5 Intensification pathway scenario analysis

The cropping system for each farm type defines the baseline scenario and is referred to as the current farmer practice (FP). We considered CA principles as the varying management scenarios under investigation given their potential to deliver ecological intensification in smallholder cropping systems in the different farm types. We quantify their productivity, GHG emission or sequestration potential to determine their suitability in redesigning those smallholder cropping systems deliver ecological intensification. The scenarios were as follows, scenario 1, considers the adoption of minimum soil disturbance through no till (FP+NT). Scenario 2 (S2), considers the adoption of crop residue retention only in cropping fields (FP+RR). Scenario 3 (S3), considers the adoption of cover crops only (FP+CC). Scenario 4 (S4), considers the adoption of cover crops and minimum soil disturbance through no till (FP+CC+NT). Scenario 5 (S5), considers the adoption of residue retention and minimum soil disturbance through no till (FP+RR+NT). Scenario 6 (S6), considers the adoption of residue retention and residue retention and cover cropping no till (FP+CC+RR). Scenario (S7), considers the adoption of the full CA package of residue retention, cover cropping and no till to the current farmer practices (FP+NT+CC+RR).

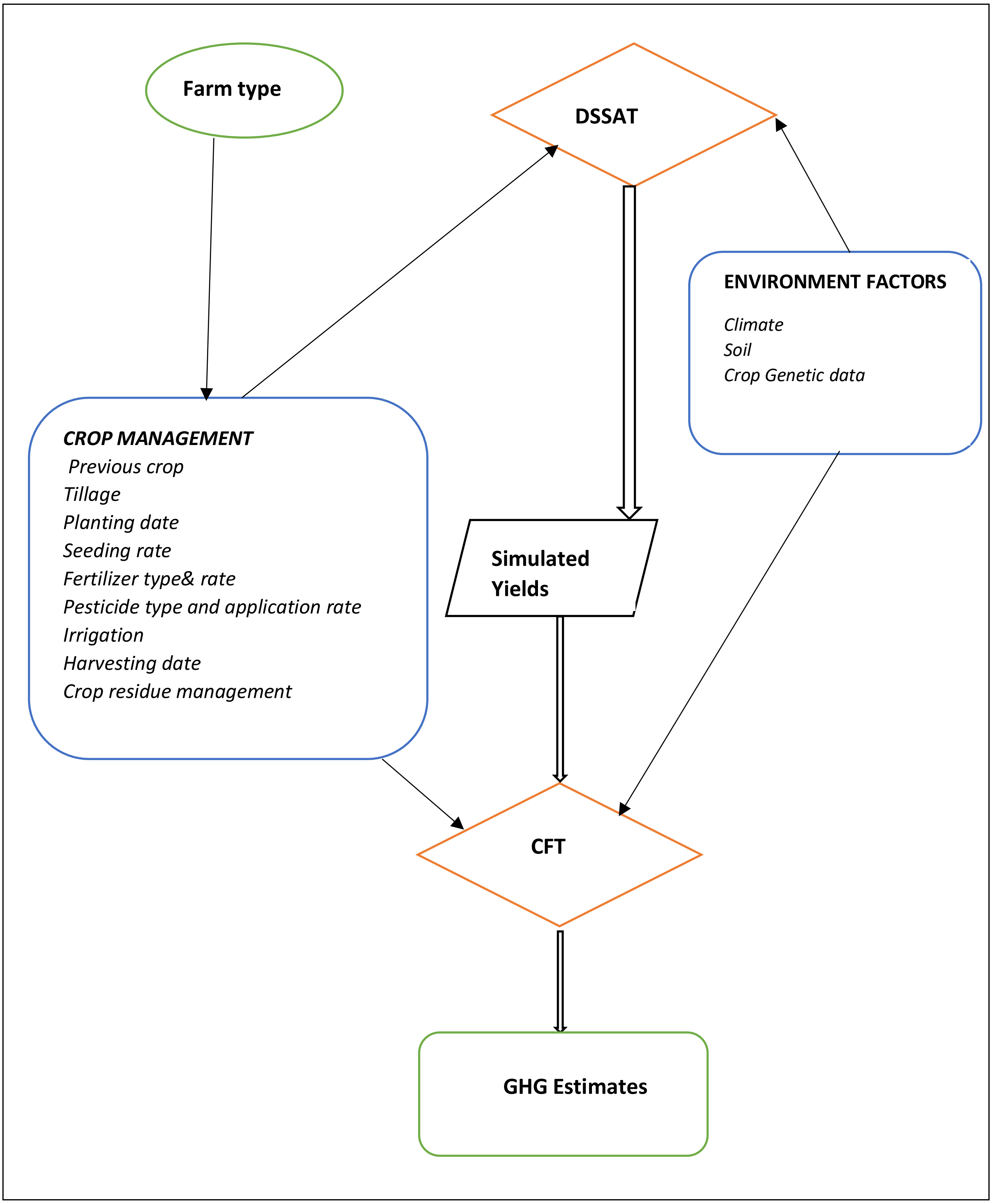

*Figure 5.1. A conceptual flow diagram of the biophysical modelling approach used to investigate crop yields and GHG emissions in maize based cropping systems in different farm types in rural South Africa.*

### 5.2.6 DSSAT model input data

DSSAT requires at least four sets of data encompassing crop, crop management, soil and daily weather to simulate crop yields.

#### 5.2.6.1 Daily weather data

DSSAT requires the following daily weather variables namely daily maximum and minimum temperatures (°C), rainfall (mm), and solar radiation ($MJm^{-2}d^{-1}$). Those variables were obtained from South African Weather Service (SAWS) for the period 2000–2015 for both Ha Lambani and Amathole.

#### 5.2.6.2 Soil profile data

The soil data describing soil texture, organic matter, mineral and nutrient and soil water dynamics is also required to run DSSAT. At each study location, relevant physical and chemical parameters of the upper 120 cm of the soil profile were obtained from literature. In Ha Lambani, soil characteristics were defined in accordance to Mzezewa et al., (2011). In Amathole, soil characteristic were defined according to Fanadzo et al., (2010). The physical and chemical parameters are summarised in Table 5.3 and 5.4.

*Table 5. 3: Soil data used to calibrate the DSSAT v4.6 model for Ha Lambani*

| Characteristics | 0-30 cm | 30-120 cm | >120 cm |
|---|---|---|---|
| Lower limit ($cm^3cm^{-3}$) | 0.12 | 0.12 | 0.13 |
| Upper limit ($cm^3cm^{-3}$) | 0.26 | 0.26 | 0.29 |
| Saturation ($cm^3cm^{-3}$) | 0.49 | 0.49 | 0.49 |
| Extractable water ($cm^3cm^{-3}$) | 0.14 | 0.14 | 0.16 |
| Root distribution ($cm^3cm^{-3}$) | 0.78 | 0.42 | 0.11 |
| Bulk density ($gcm^{-3}$) | 1.1 | 1.1 | 1.20 |
| pH | 5.5 | 5.4 | 5.3 |
| Nitrogen (%) | 0.06 | 0.06 | 0.09 |
| Organic carbon (%) | 1.94 | 1.09 | 1.7 |

*Table 5.4: Soil data used to calibrate the DSSAT v4.6 model for Amathole*

| Characteristics | 0-30 cm | 30-120 cm | >120 cm |
|---|---|---|---|
| Lower limit ($cm^3cm^{-3}$) | 0.137 | 0.137 | 0.06 |
| Upper limit ($cm^3cm^{-3}$) | 0.27 | 0.27 | 0.16 |
| Saturation ($cm^3cm^{-3}$) | 0.38 | 0.38 | 0.27 |
| Extractable water ($cm^3cm^{-3}$) | 0.14 | 0.14 | 0.16 |
| Root distribution ($cm^3cm^{-3}$) | - | - | - |
| Bulk density ($gcm^{-3}$) | 1.6 | 1.6 | 1.6 |
| pH | 6.0 | 6.0 | 6.0 |
| Nitrogen (%) | 0.13 | 0.05 | 0.01 |
| Organic carbon (%) | 0.7 | 0.22 | 0.02 |

### 5.2.6.3 Crop management data

DSSAT requires information on tillage systems, planting dates, planting density, planting depth and row spacing, type of fertilizer applied, amount and frequency of fertilizer application, irrigation amount and frequency and harvesting dates. Maize is usually sown in October in Amathole and in November in Ha Lambani. Maize is sown in rows 90 cm apart, in-row spacing of 30 cm and at a depth of 5 cm. Maize is usually grown under dryland conditions hence irrigation is not applied. The other crop management details of tillage, fertilizer application rates, harvesting dates were collected from the farmers from the different farm types (Table 5.1 and 5.2).

### 5.2.6.4 Crop data

Effective calibration of the DSSAT model would include evaluation of the model's ability to simulate phenological aspects such as emergence, silking and maturity dates for each crop and season and location. Such data was however not available from farmers, hence we relied on relevant data from other studies including e.g. Zinyengere et al., 2014 and Zinyengere et al., 2015. The calibration was made using a Trial and Error method by setting a small change (i.e., ± 5 %) of each parameter. The Root Mean Square of Error (RMSE) between the simulated and observed grain yields was used to find the best matched coefficients.

## 5.2.7 DSSAT Model settings

### 5.2.7.1 Model calibration of farm type cropping systems

The study utilised soil data, crop management, grain and above ground biomass yield to parameterise and calibrate the DSSAT model for each of the different farm type at each location. The Root Mean Square Error (RMSE) approach was utilised to evaluate the DSSAT models' ability to simulate the current cropping systems conditions. The approach compared farmer measured grain and biomass yield with model simulated yield for the three growing seasons 2000/1 to 2002/3. The RMSE values were computed using the equation (1):

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}(Si-Mi)^2}{n}}$$

Where n is the total number of data, S and M represent the simulated and measured values respectively.

A RMSE of less than 30 % is an indication of the model satisfactory ability to simulate the cropping systems, with 0-10 %, 10-20 % and 20-30 % being ‘excellent’, ‘good’ and ‘fair’ respectively (Moriasi et al., 2007). Calibration undertaken in this study showed that the RMSE across all parameters, crops and locations were under than 30 %, with some even under 10% (Table 5.5 and 5.6). The calibrated DSSAT model was used to simulate maize yields based on local parameterisation and farm type agronomic characteristics. We simulated crop yields of each farm type cropping system for the 15 growing seasons running from 2000/1 to 2014/15. In addition, we simulated for the same period potential yields for each scenario in each farm type at both locations. Farm type and scenario yield results were compared using one-way analysis of variance (ANOVA). Difference between farm types and scenarios in farm types were performed using Fisher’s least significant difference (LSD) when P<0.05.

*Table 5.5: Root mean square error (RMSE) values from the calibration of DSSAT model based on the maize grain and total biomass yields for Ha Lambani*

| Farm type | Grain yield (%) | Above ground biomass (%) |
|---|---|---|
| Cereal and livestock | 28 | 16.7 |
| Horticulture | 18.5 | 8.1 |
| Off farm income | 23.4 | 11.4 |

*Table 5.6: Root mean square error (RMSE) values from the calibration of DSSAT model based on the maize grain and total biomass yields for Amathole*

| Farm type | Grain yield (%) | Above ground biomass (%) |
|---|---|---|
| Cereal and livestock | 25.2 | 11.2 |
| Horticulture | 27.3 | 14.7 |
| Cooperative | 27.6 | 17.9 |
| Social welfare and struggling subsistence | 15 | 26.6 |

### 5.2.8 Calculation of greenhouse gas emissions at field level

The CFT was used to estimate GHG emissions per unit area and per unit crop yield for the different maize cropping systems. The CFT requires data encompassing characteristics of the land where the selected crop is grown (i.e. latitude/longitude, climate, annual average temperatures), soil characteristics (i.e. soil texture, soil type, organic matter content and soil pH), crop management information (i.e. planting dates, inputs applied eg fertilizer type and rates, agrochemicals type and rates, tillage systems, irrigation, harvesting dates and crop residue management) fuel and energy used and crop yield information to estimate GHG emissions in cropping systems.

Data for characteristics of the land where the selected crop where grown where obtained from literature as described in the previous section 5.2.1 by Ubisi et al., (2017) for Ha Lambani and by Chari et al., (2018) for Amathole. The information about soil characteristics (texture, pH, organic matter content, etc) were extracted from previous research done in Alice, Amathole District by Fanadzo et al. (2010), in Ha Lambani, Vhembe District by Mzezewa et al., (2011) and is summarised in Table 5.3 and 5.4. Crop management information were obtained from the field surveys and farmer interviewers and is summarised in Table 5.1 and 5.2. In our case, only cooperatives farms, in Amathole and horticulture-based farms in the two study areas use tractor drawn implements while all the other farm types rely on animal draught power for field operations. Although livestock is not carbon neutral, the CFT only accounts for GHG emissions directly related to crop production, as such emissions from livestock are not accounted for in this study. This is a limitation because most smallholder farmers use draft power for tillage operations. As such, animal draft power as a source of energy was not included in the calculation for these types of farms. Irrigation was not included as these farmers operate under dryland conditions. DSSAT simulated maize yields for each farm type were input into CFT.

We calculated farm type GHGs emissions of current farm practices (FP) to identify the emissions at the farm type level. Each farm type was run separately and the mean GHGs emissions were computed. We accounted for GHG related to farm management only and did not account for processing or transport beyond the farm gate. Two metrics were determined for each agricultural season running from 2000/1 to 2014/15 namely, the quantity of greenhouse gases emitted per hectare and the quantity of greenhouse gases emitted per unit crop yield. The maize yields simulated under CA scenarios described above were input into CFT to estimate the GHG emissions or sequestration potential per hectare and per crop yield of the various cropping system scenarios. GHGs emissions were compared among different farm types and scenarios results using one-way analysis of variance (ANOVA). Differences between farm types and between scenarios within farm types were explored using Fisher's least significant difference (LSD) when the ANOVA showed a significant difference between groups *(*$P < 0.05$*)*.

### 5.2.9 Land use efficiency

To assess the potential of redesigned cropping systems to ecologically intensify across farms, we used the land-use efficiency indicator. It estimates the amount of land required to produce a unit of crop. Instead of measuring tonnes produced per hectare, land use efficiency measures the number of hectares required to produce a tonne of crop.

## 5.3 Results

### 5.3.1 Current yields and GHG emissions in different farm types and locations

Simulated maize crop yields using the suite of farming practices described above varied significantly in farm types ($P < 0.05$) in both study locations (Table 5.7 and 5.8). Maize yields simulated using farming practices described above were estimated to have a positive (undesirable) GHG emissions, both based on per hectare and per unit grain yield produced (Table 5.7 and 5.8). In Amathole, cooperative farms and the struggling subsistence and social welfare dependent farms were estimated to have the highest emissions per hectare of 1538 $kgCO_2e\ ha^{-1}$ and 932 kg $CO_2e\ ha^{-1}$ respectively. In Amathole, cereal and livestock farms were estimated to have the lowest emissions per hectare of 351 $kgCO_2e\ ha^{-1}$ while in Ha Lambani the off-farm income dependent farms were estimated to have the lowest emissions per hectare of 378 $kgCO_2e\ ha^{-1}$. However, in Amathole and Ha Lambani the estimated GHG emissions per unit crop yield showed that cereal and livestock farms have the lowest GHG emissions per unit crop yield of 660 $kgCO_2et^{-1}$ and 440 $kgCO_2et^{-1}$ respectively.

*Table 5.7: Simulated maize crop yields, GHGs emissions per hectare and per unit of crop yield in Ha Lambani, Limpopo*

| **Farm type** | **Simulated average yields ($kgha^{-1}$)** | **Estimated GHG emissions per hectare ($kgCO_2eha^1$)** | **Estimated GHG emissions per tonne crop yield ($kgCO_2et^{-1}$)** |
|---|---|---|---|
| Cereal and livestock (CL) | $865^a$ | $572^a$ | 660 |
| Horticulture (Hort) | $1039^a$ | $1012^b$ | 970 |
| Off farm income (OFI) | $458^b$ | $378^c$ | 830 |
| LSD | 245 | 33 | 460 |
| P value | 0.00 | 0.00 | 0.085 |

*Table 5. 8: Simulated maize crop yields, GHGs emissions per hectare and per unit of crop yield in Amathole, the Eastern Cape*

| **Farm type** | **Simulated average yields ($kgha^{-1}$)** | **Estimated GHG emissions per hectare ($kgCO_2eha^1$)** | **Estimated GHG emissions per tonne crop yield ($kgCO_2et^{-1}$)** |
|---|---|---|---|
| Cereal and livestock (CL) | $796^a$ | $350^a$ | $440^a$ |
| Horticulture (Hort) | $1122^a$ | $712^b$ | $630^b$ |
| Cooperative (CP) | $528^b$ | $1538^c$ | $2910^c$ |
| Social welfare and struggling subsistence (SWSS) | $228^c$ | $932^b$ | $4090^d$ |
| LSD | 258 | 241 | 110 |
| P value | 0.00 | 0.00 | 0.00 |

### 5.3.2 The impact of conservation agriculture practices on yield and GHG emission

The figures 5.2 and 5.3 show yield per hectare on the y- axis and GHG emissions per hectare on the x- axis of the various crop management scenarios. They illustrate on the right-hand side crop management scenarios that are positive emitters of GHG (undesirable cropping scenarios) while on the left-hand side crop management scenarios that are negative emitters of GHG (desirable cropping scenarios). A combination of high yield and negative emissions, "desired crop management scenarios" would be on the top left and a combination of low yield and high emissions, "undesired crop management scenarios" would be on the bottom right. The trend building up from figures 5.2 and 5.3 show farmer practices (FP) on the bottom right (undesired) and the full CA package (FP+NT+CC+RR) on the top left (desired), illustrating concurrent yield and GHG emission improvement from integrating CA practices to the farmer practices.

More specifically, our simulations (Fig. 5.2 and 5.3) show that integrating conservation agricultural practices of no till (NT), residue retention (RR) and crop diversification and associations through rotations, intercropping or cover cropping (CC) to the current farmer practices (FP) alone or in combination significantly impacts both crop yield and GHG emissions in cropping systems. Simulations showed that integration of residue retention (FP+RR) and cover cropping (FP+CC) to the current farmer practices (FP) alone significantly improved crop yields ($P < 0.05$) while the no till (FP+NT) practice resulted in lower yields when compared to the current farmer practice across all farm types and locations. With regards to GHG emissions, our estimates show that integrating the no till (FP+NT) practice and cover cropping (FP+CC) significantly lowers GHG emissions while the residue retention practice (FP+RR) significantly contributes to increased GHG emissions when compared to current farmer practices.

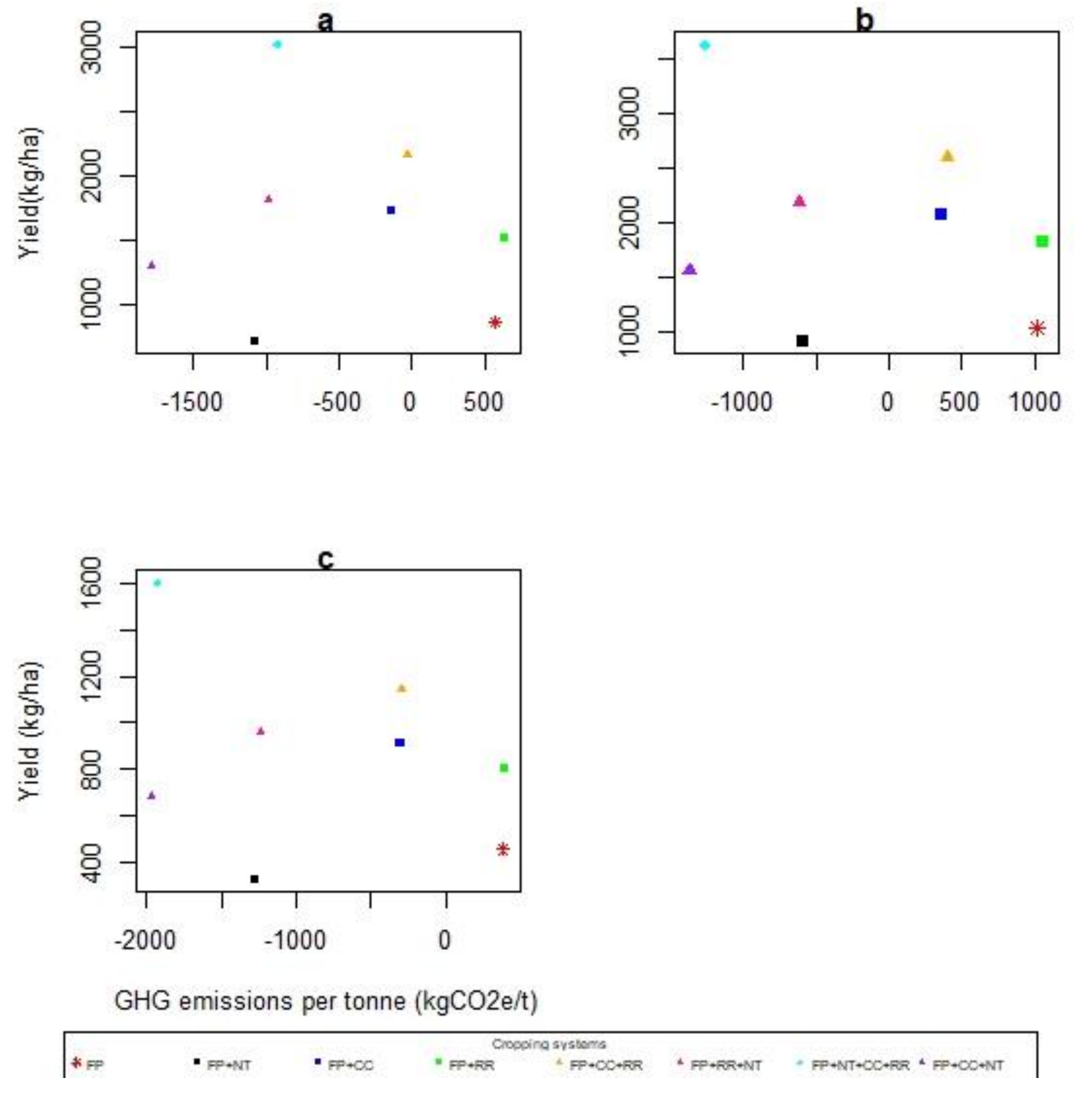

*Figure 5.2 Modelled impact of different crop management scenarios on maize crop yields and GHG emission per hectare in Ha Lambani: a) cereal & livestock farms, b) horticulture farms and c) off farm income-based farms*

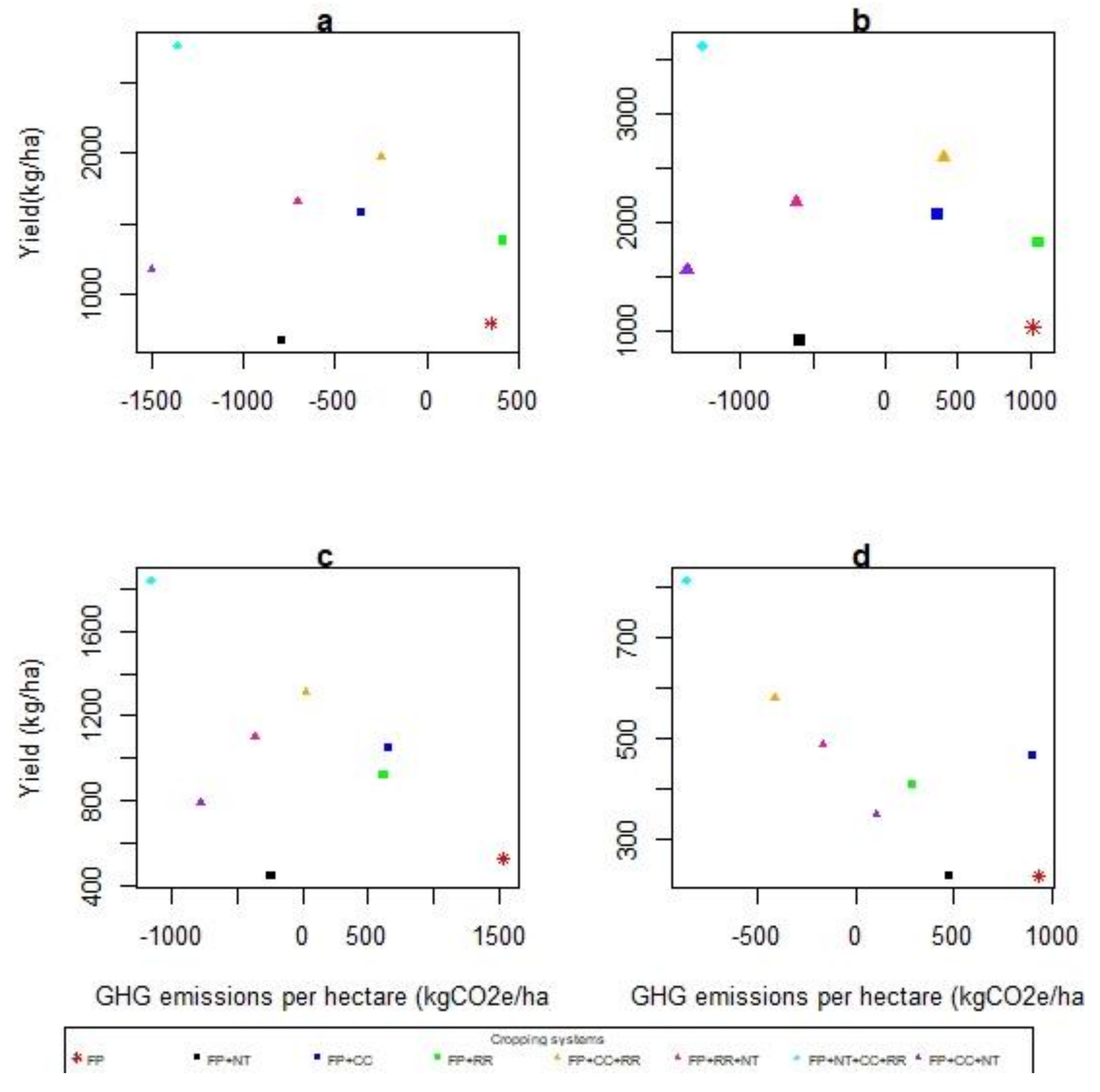

*Figure 5.3 Modelled impact of different crop management scenarios on maize crop yields and GHG emission per hectare in Amathole: a) cereal & livestock farms, b) horticulture farms, c) cooperative farms and d) social welfare and struggling subsistence farms.*

Our results showed that when CA practices are used in combination for example when residue retention and cover cropping (FP+CC+RR), or when residue retention and no till (FP+RR+NT) or when cover cropping and no till and (FP+CC+NT) are combined and included in the current farming practices, crop yields are significantly improved ($P< 0.05$) across all farm types and GHG emissions are significantly lowered. Beyond understanding the impact offered by the integration of single CA practices our results confirm that when CA practices are used in combination, crop yields are significantly improved and GHG gas emissions are significantly lowered when compared to when CA practices are used alone. For example, when no till is integrated with residue retention (FP+RR+NT) or when integrated with cover crops

(FP+CC+NT) significant yield gains and GHG emissions are lowered when compared to FP+NT. A similar trend was observed for the following cropping scenarios FP+RR+NT and FP+CC+RR when compared to FP+RR and when FP+CC+NT and FP+CC+RR are compared to FP+CC cropping scenarios. Ultimately, the full CA package (FP+NT+CC+RR) showed to be the most desired cropping scenario (found on the top left of figure 5.2 and 5.3) as it showed significant potential to improve crop yields ($P<0.05$) and lower GHG emissions ($P<0.05$) in all farm types across the locations.

### 5.3.3 Impact of conservation agricultural practices on land use efficiency per unit yield and GHG emissions per unit yield

The figures 5.4 and 5.5 show land use efficiency per tonne produced on the y- axis and GHG emissions per tonne on the x- axis of the various crop management scenarios. They illustrate on the right-hand side crop management scenarios that are positive emitters of GHG per tonne produced (undesirable crop management scenarios) while on the left-hand side are crop management scenarios that are negative emitters of GHG per tonne produced (desirable crop management scenarios). A combination of high land use efficiency and negative GHG emissions per tonne produced would be on the bottom left (desired crop management scenarios) and a combination of low land use efficiency and high GHG emissions per tonne produced, would be on the top right (undesired crop management scenario). The trend building up from figures 5.3 and 5.4 show farmer practices (FP) on the top right (undesired) and the full CA package (FP+NT+CC+RR) on the bottom left (desired), illustrating concurrent land use efficiency and GHG emission (carbon sequestration) improvement from integrating CA practices to the farmer practices. More specifically, our results show that CA practices can contribute to reducing pressure on land and help deliver agricultural intensification with low GHG emissions per unit yield. Figure 5.4 and 5.5 show that the integration of residue retention (FP+RR) and the integration of cover crops (FP+CC) have the potential to produce a tonne of maize on a smaller land area as compared to the normal farmer practice (FP) across all farms and locations. Similarly, figure 5.4 in Ha Lambani, FP+RR cropping scenarios show a similar trend where across the farms.  However, the integration of no till (FP+NT) is expected to require a larger land area to produce a tonne of maize, compared to the normal farmer practice (FP) across all farms and locations. Figure 5.4 and 5.5 showed that the integration of no till (FP+NT) or the integration of cover crops (FP+CC) or the integration of residue retention has the potential to produce maize with low GHG emissions per unit yield when compared to the normal farmer practice across the farms and study locations.

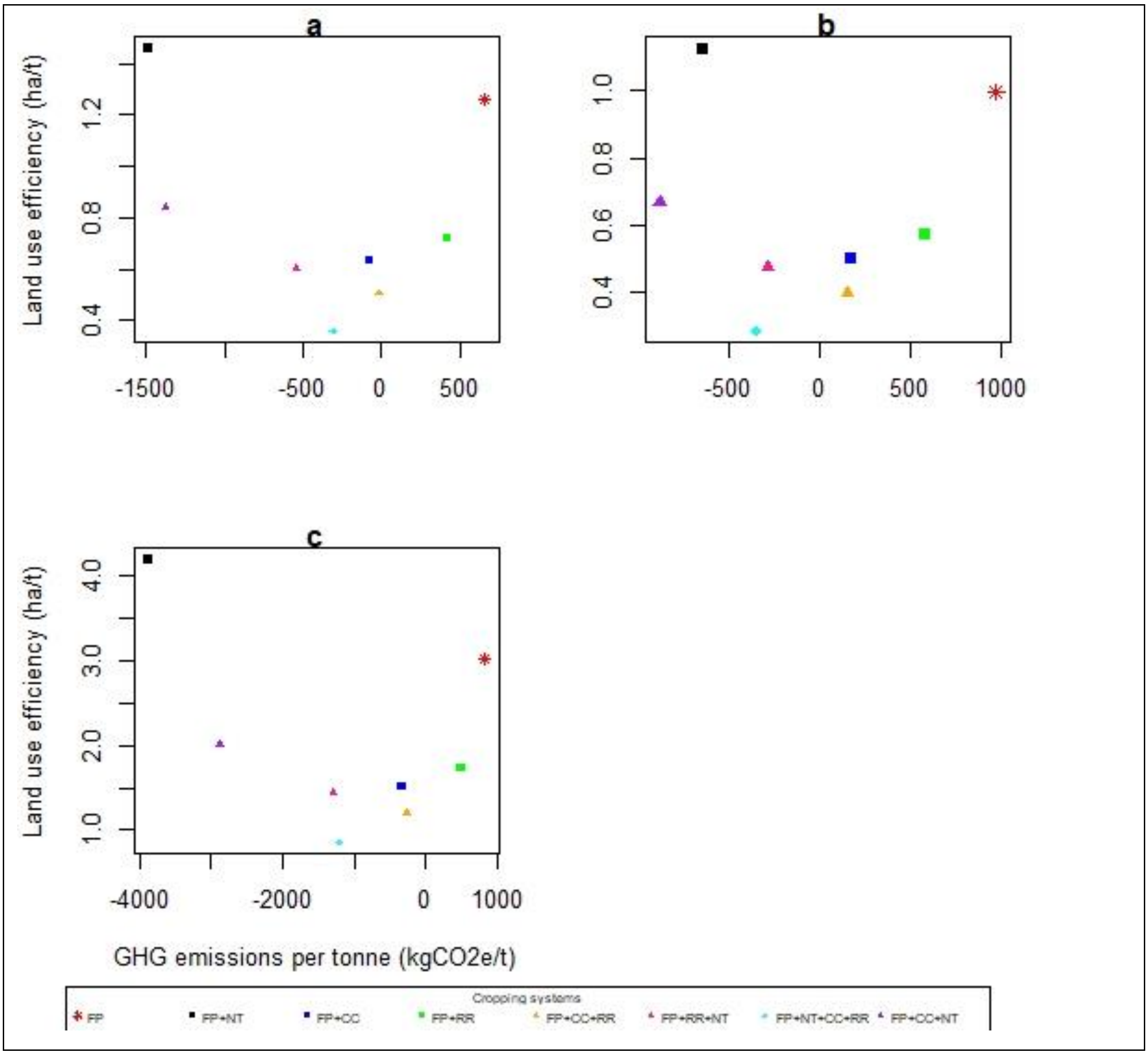

*Figure 5.4. Potential impact of different crop management scenarios on land use efficiency and GHG emissions per tonne of maize in Ha Lambani. a) cereal and livestock-based farms, b) horticulture-based farms; and c) off farm income-based farms.*

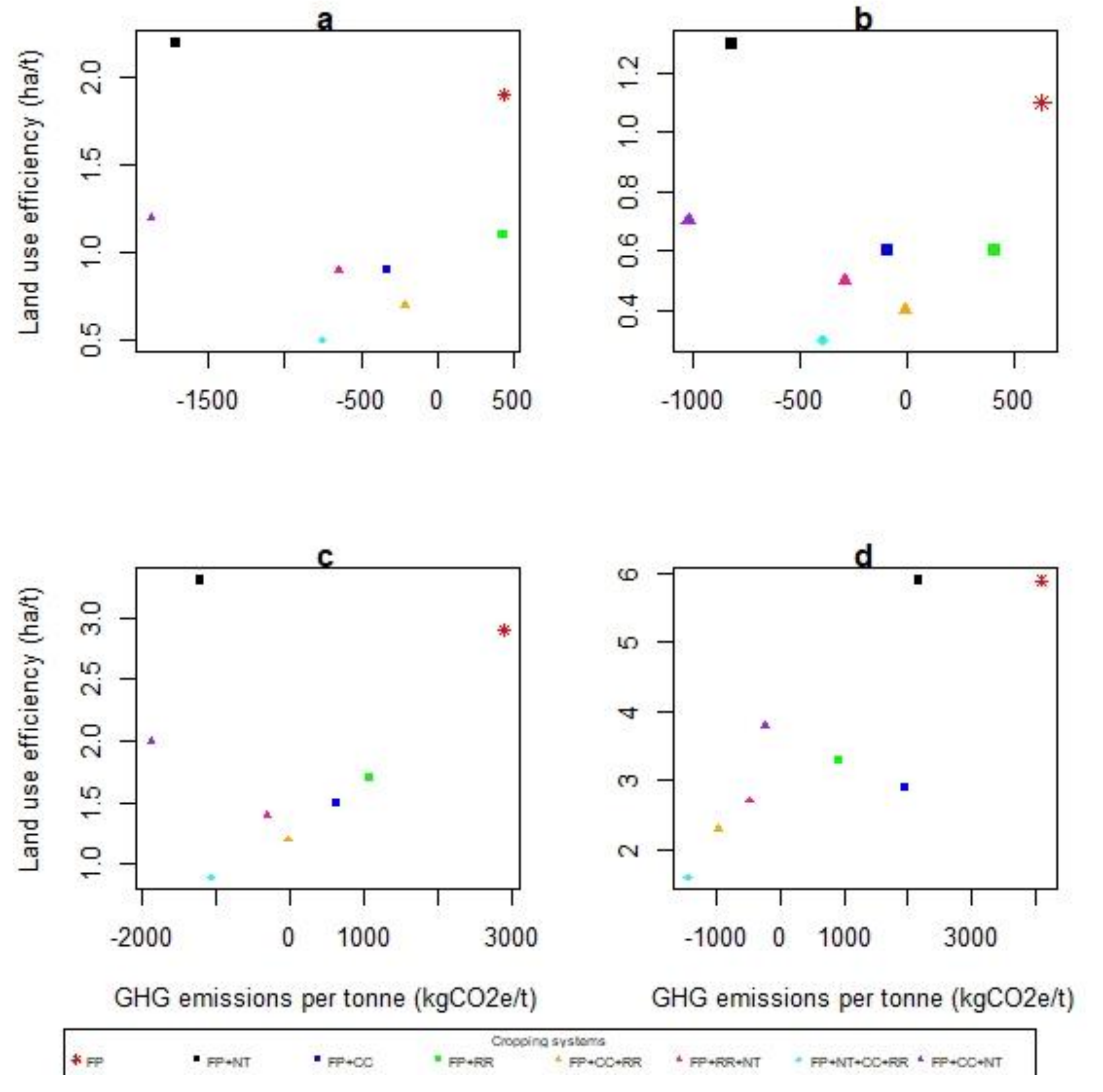

*Figure 5.5. Potential impact of different crop management scenarios on land use efficiency and GHG emissions per tonne of maize in Amathole. a) cereal and livestock-based farms, b) horticulture-based farms; c) cooperative based farms and d) social welfare and struggling subsistence farms.*

Furthermore, our results (Figure 5.4 and 5.5) show that using a combination of CA practices, for example, FP+RR+NT, FP+CC+NT, FP+CC+RR or FP+NT+CC+RR has the potential to significantly intensify maize cropping systems across farm types and location. Beyond understanding the impact offered by the integration of single CA practices our results confirm that when CA practices are used in combination, land use efficiency is significantly improved and GHG emissions per unit crop yield are significantly lowered when compared to when CA practices are used alone. For example, when residue retention is integrated with no till residue (FP+RR+NT) or when integrated with cover crops (FP+CC+RR) land use efficiency is significantly improved and GHG emissions per unit yield are significantly lowered when compared to FP+RR. Ultimately, results showed that the full CA package of FP+NT+CC+RR has the potential to significantly improve land use efficiency and GHG emissions per unit yield when compared to the farmer practice and other cropping scenario combinations across the farms and locations.

## 5.4. Discussions

### 5.4.1 Maize based cropping systems and their implication for agricultural intensification

Maize was the main crop grown in the different types of smallholder farms studied here, and it was mainly for subsistence purposes. Research in SSA has mainly focused on yield improvement of maize based cropping systems and few studies have reported on their GHG emissions. Maize based cropping systems from different farm types in Amathole and Ha Lambani were compared in this study to provide a baseline for exploration of alternatives that concurrently lead to higher crop yields per unit area and lower GHG emissions. The simulated maize crop yields were low in all farm types ranging from 0.2 to 1.1 tha$^{-1}$ in the Amathole and ranged from 0.4 to 1 t ha$^{-1}$ in Ha Lambani. Considering the difficulties associated with increasing production extensively in smallholder agricultural systems in SSA due to issues of land constraints, the simulated current yields indicate that there is an opportunity to improve agricultural productivity through intensifying cropping systems on the current agricultural land and this may be a viable option for these smallholder farmers.

Maize based cropping systems in the different farms are net sources of GHGs per unit area. The magnitude of GHG emission per unit area varied and ranged from 350 to 1538 kgCO$_2$e ha$^{-1}$ and from 378 to 1012 kgCO$_2$e ha$^{-1}$ across farms in Amathole and Ha Lambani respectively. GHG emissions in our study were generally similar and within range to those other low input smallholder systems in SSA found by Bellarby et al., (2014); Ortiz-Gonzalo et al., (2017) and Ortiz-Gonzalo et al., (2018). Table 5.1 revealed heterogeneity in crop management strategies and agricultural input use in maize based cropping systems across all farm types. This heterogeneity in crop management determined the magnitude of these emissions. Fertilisation, tillage and crop residue management were the major emission hotspots that contributed to the magnitude of the emissions. In Amathole, the social welfare and struggling subsistence farms, despite having low inorganic or N fertiliser application rates as well as using no fossil fuels, had the highest GHG emissions per unit area, mostly because of poor crop residue management. In these farms crop residue is usually left in heaps or pits for composting thus, the decomposition of crop residue contributes significantly to GHG emissions. For similarly reasons, cooperative farms in Amathole, this poor management of crop residue contributed highly the GHG emissions. In cooperative and horticulture-based farms, tillage, fertiliser use, and fossil fuel energy mostly contributed to the high GHG emissions. In these farms, the use of inorganic fertilisers is relatively high when compared to the other farm types. In addition, machinery drawn implements associated with burning of fossil fuels contributed significantly to high the GHG emissions whilst the ploughing in of crop residue creates favourable conditions for organic matter oxidation and mineralisation, resulting in soil carbon loss and further contributing to GHG emissions.

The estimated GHG emissions per unit crop yield was high and varied significantly ($P< 0.05$) across all farm types. The magnitude of GHG emission per unit crop yield ranged from 440 to 4 090 kg$CO_2$e $t^{-1}$ and from 660 to 970 kg$CO_2$e $t^{-1}$ across farms in Amathole and Ha Lambani respectively. The current range and magnitude of GHG emissions confirm that smallholder cropping systems can improve, despite low and extensive use of external inputs across the study farm types and locations. For example, the social welfare and struggling subsistence farms had the highest farm GHG emissions per unit crop yield. The lowest crop yields per hectare and the highest GHG emissions per unit area confirm the inefficiency of the production process despite having low inorganic N application rates and no use of fossil fuels which the major drivers for GHG emissions in cropping systems are. These results concur with Bellarby et al., (2014) found out that smallholder farms concurrently had very low yields and very high GHG emissions per tonne of maize in Kenya. In these farms, poor management of crop residue contributes significantly to the estimated high GHG emissions thus contributing significantly to the inefficiency of the cropping system. Similarly, in Amathole, cooperative farms also have high GHG emissions per unit area emanating from poor management of crop residues. The low greenhouse gas emission per unit crop yield observed in cereal and livestock-based farms maize based cropping systems emanates from the fact that in these farms crop residues are exported to feed livestock hence crop residues do not contribute significantly to GHG emissions in such maize based cropping systems hence these systems are comparatively more efficient when compared to cropping systems in other farm types.

Although several scholars argue that in SSA agricultural intensification is premised to meet the increased food demand for the growing population. However, some scholars argue that in SSA agricultural intensification success depends on the increased use of inorganic fertiliser (Vanlauwe et al., 2014; Holden, 2018). Our results reveal that even farms (horticulture and cooperative based farms) that are well resource endowed i.e. farms with high N application rates compared to the other farm types (although limited), there are still experiencing low yields and high GHG emissions in their maize based cropping systems. As evidenced by the exceptionally low yields, high GHG emissions and low response to fertilizer application, the currently available resources in these farm types are either being used inefficiently or inappropriately. There is, however, a risk that agricultural intensification based on high input use of fertilisers and agrochemicals alone may further lead to an increase of agricultural GHG emissions leading to further environmental degradation, amplified climate change and overall unsustainable development of sub Saharan Africa agricultural systems.

The current relationships of low crop yields and high GHG emissions in smallholder farms can be reversed by using eco-efficient intensification solutions such as ecological intensification that utilise ecological processes to improve resource use efficiency, productivity (yield) and ensure reduced GHG emissions. As systems are already more ecological in nature (Tittonell & Giller, 2013), ecological intensification is presenting an easier implementation at a lower cost (e.g. in terms of less fertiliser) for a combined increase in yields and low GHG emissions for resource limited farmers as it aims to complement the limited external inputs or even to replace them. On this premise, it seems evident that intensification of smallholder farming systems should be based on agroecological approaches that capitalise on the available resources to improve productivity while concurrently increasing environmental sustainability.

### 5.4.2 Redesigning smallholder cropping systems to deliver ecological intensification based on CA practices

We used the modelling framework above using the three CA practices to guide in remodelling cropping systems to redesign and deliver ecologically intensive cropping systems with low GHG emissions, drawing inspiration from current strategies used by the resource constrained smallholder farmers, which indicate that cropping systems are rather ecological or close to being ecological. CA is being promoted as an agroecological approach to deliver both sustainable and ecological intensification in smallholder cropping systems. We opted to redesign the cropping systems with CA to deliver ecological intensification because of limited access, affordability and minimal inorganic fertiliser use, which is way below the recommended fertiliser application rates of the study areas. Conservation agriculture is associated with either exploitation of ecosystem services for increased food security or delivery of ecosystem services for environmental sustainability. Hence ecological intensification seemed a realistic and viable option for intensification in these type farms. Although other practices and or approaches could be explored in a similar way, we demonstrate the value of multi criteria assessment of crop management alternatives, concurrently leading to increased production and reduced GHG emissions. We had a holistic evaluation of crop yields and GHG emissions from current cropping systems in different farm types to evaluate fully the mitigation potential of CA components and CA as a package.

Our results show that integrating these three main agroecological practices in smallholder cropping systems has the potential to substantially increase yields, lower GHG emissions and increase land use efficiency in smallholder cropping systems. Redesigning smallholder cropping to retain crop residue as surface mulch on the current cropping systems (FP+RR) showed crop yields gains and land use efficiency improvement across all study farm types and locations. However, results showed that crop residue retention on the soil surface will increase GHG emissions in cropping systems. These results also concur with Rusinamhodzi et al. (2015) who observed yield gains in maize cropping systems of smallholder farmers with different resource endowments and Pugesgaard et al., (2017) who found crop residues to significantly stimulate GHG emissions in cropping systems with restricted access to fertilizers or manure. Although crop residue retention maybe associated with crop yield gains and land use efficiency, the increased GHG emissions and associated trade-offs for crop residue use as a livestock feed or as mulch for soil cover in cropping systems may make it an unsuitable cropping scenario, resulting in it being not a viable option to redesign smallholder cropping systems for ecological intensification in farms with livestock.

Our results showed that including legume cover crops (FP+CC) has the potential to increase crop yields, improve land use efficiency and at the same time lower GHG emissions in smallholder cropping across all study farm types and locations. Mupangwa, Thierfelder, and Ngwira (2017) observed that legume cover crops improved maize grain yield and the maize crop benefitted from the residual soil fertility contributed by legume cover crops. The results showed that a significant reduction in GHG emissions in cropping systems with legume cover crops and these results concur with Helene et al., (2018) who observed a significant reduction in GHG emissions from similar scenarios. Moreover, our results showed that the inclusion of legume cover crops in maize based cropping systems will likely improve land use efficiency. Legume cover crops are known to provide several ecosystem services that can benefit both cropping systems and the environment. Therefore, the use of legume cover crops in smallholder agroecosystems must develop to encourage agroecological production and contribute to the mitigation of climate change. Thus, the inclusion of legume cover crops could be a viable option to redesign cropping systems to improve productivity and environmental sustainability and deliver ecological intensification with low GHG emissions.

Our results showed the practice of no till (FP+NT) is expected not to significantly impact crop yields (P>0.05) when compared to the farmer practice (FP) across all the farm types. The practice is expected to result in low crop yields with low GHG emissions. Thierfelder et al., (2017) asserted that only when using no tillage alone yields and yield stability will not improve. According to Chivenge et al., (2007) and Masvaya et al., (2017b) in CA systems no till reduces the rate of mineralisation when compared to conventional tillage. This is because minimum soil disturbance preserves soil organic matter from decomposition. Due to the slow mineralisation of organic material or manure, which are the main sources nutrients in these resource constraints farms, nutrient supply for plant growth is limited hence the low yields observed across all farm types in the study locations. Furthermore, the labour demands associated with the no till practice has been a major constraint for adoption in smallholder cropping systems. In such a scenario where labour and land demand is high and efficiency is low Lal (2007) suggested that resource constrained smallholder farmers would be better off tilling their cropping fields to enhance the process of mineralisation of organic material to improve nutrient supply for crop growth in the short term. Although Baker et al., (2007) highlighted the controversies of the no till component of CA regarding soil carbon sequestration, our results show that the (FP+NT) practice has the potential to turn smallholder cropping systems from net sources of carbon to net sinks by helping cropping systems sequester carbon in the soil. The practice however, may not be a viable option for redesigning cropping systems as it might increase the labour burden but not crop yield. Hence seems an unlikely pathway to deliver ecological intensification in smallholder agriculture in SSA.

Results showed that using a combination of CA practices (FP+RR+NT), (FP+CC+NT), (FP+CC+RR) and (FP+NT+CC+RR) will impact positively on crop yields, land use efficiency and lowering GHG emissions across all study farm types and locations when compared to the farmer practice (FP) and when CA practices are used alone. Furthermore, results showed that using a combination of CA practices can deliver ecological intensification, in which crop and land productivity can be improved and concurrently contribute to the delivery of ecosystem services for climate change mitigation that can be harnessed to enhance environmental sustainability. Results showed that the full CA package of (FP+NT+CC+RR) has the potential to have the highest crop yields and improve land use efficiency across all study farm types and locations. Regarding GHG emissions and depending on farm type the full CA package (FP+NT+CC+RR) and the (FP+CC+NT) cropping are expected to have the lowest GHG emissions. These results are in agreement with several other studies on the effects of CA on maize yield in smallholder farms in SSA (Thierfelder et al., 2015; Ngwira et al., 2012; Nyamangara et al., 2014). As with regards to GHG emissions, these findings add to previous studies (e.g. Dendooven et al., 2012; Kimaro et al., 2016; Cheesman et al., 2016; Tellez-rio et al., 2017; Thierfelder et al., 2017), showing that using a combination of CA practices may help contribute to carbon sequestration in the soil and significantly increase soil carbon content.

CA practices are associated with several trade-offs that make the integration of the three practices into cropping systems difficult. Our results revealed that the integration of two practices can help improve yields, land use efficiency and lower GHG emissions even in farms where the integration of three practices will result in trade-offs. For example, smallholder farmers face challenges of retaining crop residue as soil cover, mainly due to competing uses for the crop residue produced, especially to feed livestock. Our results show that in such circumstances, the FP+NT+CC cropping scenario may result in significant crop yield gains, land use efficiency improvement and lowering of GHG emissions across all farm types and study locations and, may be a viable option or feasible entry point for ecological intensification especially for cereal and livestock farms where trade-offs for mulch use are expected to be significant. For some type of farms, it is impossible to adopt the no till practice due to its labour demand. Under such circumstances, our results show that the FP+CC+RR cropping scenario may result in significant yield gains, improve land use efficiency and lower GHG emissions in cropping systems. This cropping scenario may be a viable option or entry point for ecological intensification in farms where labour is a challenge especially in off farm income dependent farms who are always engaged in other non-farm activities. Integration of crop associations e.g. inclusion of legumes, cover crops and rotations has not been widely accepted and adopted by smallholder farmers due to various reasons such as, limited space, need for increased labour when planting, seed unavailability and lack of knowledge on how to grow these crops in association with their main preferred cereal crop. Under such circumstances, our results show that the FP+RR+NT cropping scenario may result in significant yield gains, improve land use efficiency and significantly lower GHG emission in cropping systems. This cropping scenario may be a viable option or feasible entry point for ecological intensification in farms that are land constrained, resource limited and where maize is grown as the main staple food.

### 5.4.3 Perspectives on the modelling framework

The study aimed to demonstrate how a farm typology, crop model and a farm focused calculator can be combined to explore and assess productivity and sustainability. The study was based on simple localised farm survey data, crop modelling using DSSAT and estimation of the GHG emissions using the CFT. The survey identified practices used in maize based cropping systems through snowball sampling of farms developed through the expert-based typology approach. Although they were small sample sizes for farm types in each study location and this may have caused imperfect matching and bias of cropping systems attributes, we were able to show the heterogeneity of maize cropping system attributes in smallholder farming systems. This can, however, be improved through increasing the sample size of surveyed farm types. In this study, we used DSSAT to simulate detailed farm management practices, allowing simulations to reflect detailed farm management strategies in cropping systems. Although DSSAT requires a large data set for correct parameterisation, calibration and validation procedures which were sometimes not available for the study areas. We relied on secondary data from other studies and sources for calibrations to improve the accuracy and reliability of our crop yield simulations. The CFT was the best tool we could use to estimate on farm GHG emissions using our data and it was best able to factor in the different agronomic practices and strategies for the different farm types. However, GHG calculators are developed in developed countries, programmed with default emission factors (EF) and other model parameters from these developed countries (Olander et al., 2014), as such GHG calculators may overestimate or underestimate GHG emission sources when compared against field based measurements and thus may not accurately quantify and estimate agriculture related GHG emissions in smallholder farming systems in SSA (Richards et al., 2016). We demonstrated that coupling the CFT with yield estimates of that crop management scenarios helped improve GHG emission quantification of a particular crop management scenario. It should be recognised that any bias whether positive or negative is of less significance when comparing cropping systems or management practices from the same country or region with each other. However, in our study, the samples for the different crop management scenarios were from the same country as such most of the variability in GHG emissions was introduced by the crop management characteristics and not to such an extent by EF and model parameters. Although the models used in this study have features that are needed for the estimation of crop yields and GHG emissions. We found that all of them have limitations and need to be improved to capture the complex nature of smallholder cropping systems that are interdependent with their livestock production systems. For example, crop residue management is not fully accounted in certain cases where it is removed to feed livestock and the contribution of GHG emissions from livestock in cases where they are used for draught power. This lack of full consideration of scale is a common limitation. These limitations are a great obstacle to accurate quantification of GHG emission to better understand the sustainability of smallholder agricultural practices and production chain towards agricultural intensification. Overall, the modelling framework allowed the identification of practices and a combination of practices, aiming for most realistic and achievable food and GHGs efficient production systems in different farm types. The modelling framework will help guide policy simulations and scenario analysis, especially where agricultural development programs involve preference of one sustainability dimension over another.

## 5.5. Conclusion

The full integration of three CA practices of no till, residue retention and crop associations have the potential to improve crop yields, lower GHG emissions and turn maize cropping systems into net sinks of carbon. In addition, stepwise integration of CA practices alone or in combination also showed significant potential to improve crop yields and lower GHGs emissions hence can be a possible strategy to address trade-offs associated with uptake of CA practices in smallholder cropping systems. Furthermore, integrating these three practices showed that ecosystem services for climate change regulation can be harnessed to enhance environmental sustainability. Our analysis suggests that productivity and environmental sustainability may be improved through proper agronomic management (tillage, crop associations and proper crop residue management) even when fertiliser rates are not increased. These results provide valuable insights into the ongoing debate on how to intensify smallholder cropping systems to improve crop yields and food security without a substantial increase in external inputs such as fertiliser which have the potential to increase GHG emissions and ultimately impact on the environment and the climate system. Hence the paradigm of ecological intensification can be a viable low cost and low carbon intensification option for smallholder cropping systems in SSA.

Moreover, the research provided an environmentally oriented indicator of cropping system efficiency in the form of GHGs emissions which has been lacking to capture farmers initiatives towards mitigation and reducing the negative impacts of their farm management practices on the environment. The productivity and sustainability assessments provide valuable insights and help policy makers to easily benchmark and rank farm performances, as well as monitor progress over time. The findings on the key drivers of sustainability in smallholder cropping systems will help agricultural scientist, policy makers and other agricultural stakeholders to identify and tailor effective CA packages and interventions to suite farm type level needs to improve farm type sustainability. Therefore, rather than intensification focusing on increasing the use of inorganic fertilisers and agrochemicals, more focus should be on improving the resource use efficiency of current resources in cropping systems. We recommend that future research and analysis is required into several aspects of crop yield and GHG emission quantification to improve accuracy of simulated crop yields and estimated GHG emissions, this includes measurement of crop yields and GHG emissions from soils from different crop management scenarios using varied inputs in different locations to provide data for correct parameterisation, calibration and validation procedures which were sometimes not available for the study areas. Furthermore, this field data needs to be intergrated into a farm scale study so as to quantify and capture the benefits across the farm as smallholder farms are complex and agricultural systems are interdependent.

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# CHAPTER 6

# CONCLUSION

## 6.1 Outline of my conclusion

In this Chapter, I reflect on previous chapters (6.2). On the basis of the main findings (6.3), I synthesise and construct argumentation that lead to a novel assessment of ecological intensification in the context of smallholder farming systems in South Africa, paying particular attention to its suitability, applicability and its contribution to environmental sustainability in the face of climate change in smallholder farming systems (6.4). Finally, I make recommendations on how ecological intensification could be implemented for better uptake. I propose future research questions and work, which would continue to push boundaries towards appropriate transformation (6.5).

## 6.2 Reflection of my previous chapters

In Chapter 2, 1 reviewed and characterised conventional intensification based on its suitability, sustainability and most importantly its limitations and challenges in smallholder farming systems in SSA. Driven by the need for increased agricultural production and environmental sustainability to achieve sustainable food security I highlight that new forms of sustainably oriented agricultural intensification namely sustainable and ecological intensification have emerged. I later discussed the suitability, potential benefits and steps that must be taken for ecological intensification to guide SSA remodelling of smallholder farming systems towards sustainable increased food production. In chapter 3, I used a framework encompassing an expert-based farm typology to depict farming systems heterogeneity and understand both the biophysical and socio-economic constraints of the current smallholder cropping systems. I present how farming systems analysis of challenges and constraints helps to identify and link specific ecosystem services with suitable ecological intensification options to address farm type challenges and constraints. In chapter 4, I identify options or practices that can be used to foster ecological intensification. I explore their uses or roles in smallholder food production systems. Using the Unified Theory of Acceptance and Use of Technology (UTAUT) framework I show that besides the productivity potential, other factors such as ease of use, socio-economic issues as well as enabling actors must be considered to enable acceptance and use of ecological intensification options. In Chapter 5, I introduce a modelling framework that encompasses a farm typology, a crop model and a farm focused GHG calculator to assess cropping system performance and efficiency. I use this framework to identify situations where productivity can be increased without or with minimal negative effects on the environment to ensure environmental sustainability. This assessment helps to guide the remodelling or to redesign cropping systems to deliver ecological intensification to achieve both productivity, adaptation, mitigation and overall sustainability at the farm level.

## 6.3 Key findings

Smallholder farming systems, due to their importance in rural development in SSA, must seek long term sustainable production increases to tackle food security and poverty reduction. The thesis aimed to assess the value of ecological intensification of agriculture to improve food production systems, livelihoods and environmental sustainability in smallholder farming systems in the face of climate change and variability. Key findings found in chapter 2, 3, 4 and 5 are as follows;

### 6.3.1 The potential of ecological intensification in diverse smallholder farming systems

In chapter 2, I showed that ecological intensification is more clearly defined than sustainable intensification, with a better theoretical basis and seems a promising option for African smallholder farmers operating under harsh environmental and socio-economic conditions with limited resources. I advocate for ecological intensification as a better fit and a promising paradigm for remodelling smallholder farming systems both in response to existing capacities, as well as the immediate need for long term sustainable production increases and environmental sustainability in SSA. Transformation of smallholder agricultural systems to achieve food security will require agricultural intensification options that have the potential to improve the resource use efficiency of the limited external inputs, soil fertility, pest, and weed suppression, reduce risk of crop failure, improve overall crop productivity and environmental sustainability. Ecological intensification options or approaches have the potential to address the above-mentioned constraints to increased crop production and yields and achieve some of the goals such as environmental sustainability, particularly in resource constrained African smallholder farming systems and communities. Finally, I suggest that moving towards ecological intensification requires a holistic view and understanding of smallholder farming system attributes and challenges.

### 6.3.2 Developing pathways to ecological intensification through incorporating and exploiting ecosystem services

In chapter 3, I explore farming systems attributes and challenges using smallholder farmers from Ha Lambani in Vhembe District in Limpopo Province SouthAfrica as a case study. I showed the heterogeneous nature of smallholder farming systems and communities through an expert-based classification of farmers and farms which led to the identification of different smallholder farm types. The classification revealed the heterogeneity of cropping systems patterns and the variability of cropping systems challenges and constraints within smallholder farming communities. The study confirmed the low input nature of smallholder farming systems. This low input nature means confirmed that farming systems have remained ecological, maintained and enhanced by supportive and regulatory ecological processes steered through location-specific indigenous knowledge. Ecological intensification seeks to ensure long term productivity and sustainability through the restoration of biodiversity and a full array of ecosystem functions and services that support food production and human well-being. I show that identifying and understanding smallholder cropping systems challenges and constraints could help link and harness ecosystem services that could be fully and properly exploited to deliver ecological intensification that addresses specific farm type challenges and constraints to improve and ensure the productivity of smallholder farming systems.

### 6.3.3 Factors enabling acceptance and use of ecological intensification technologies in smallholder farming systems

In chapter 4, I explored the relevance, the applicability and the feasibility of ecological intensification options in smallholder farming systems using the UTAUT framework. Farmers perceived ecological intensification options to be relevant as they helped address pests, soil fertility, soil and water conservation and seasonal variability issues in smallholder cropping systems. Yet despite, this relevance, their use and acceptance were limited by other factors such as ease of use, social influence and enabling actors which equally have a strong influence compared to productivity potential in determining acceptance and use of these ecological intensification options in smallholder farming systems. Thus, when introducing intensification options, these factors must also be explicitly evaluated in the light of smallholder farmers' production objectives, values, norms, institutions and among others.

### 6.3.4 Assessing productivity and environmental sustainability to deliver ecological intensification in smallholder farming systems

High GHG emissions from the current low yielding maize-based cropping systems in smallholder farms indicate the overall cropping system inefficiency across all farm types in smallholder agriculture. I then explored the productivity and environmental sustainability potential of agroecological practices of CA to help redesign and deliver ecological intensification in different farm types in smallholder agricultural systems. Although results confirmed that using a full package of CA practices offers the best potential to increase crop yields, land use efficiency and sequester carbon, we acknowledge the need of smallholder agricultural systems to compromise with available time, financial, human and other resources. I consequently explored the combined value of sub grouping CA practices for productivity and environmental sustainability concurrently. Guided by farmers' vision and resource availability, various choices remain to concurrently improve production and ensure environmental sustainability.

## 6.4 Implications of findings

Agricultural intensification is considered as a key alternative to improve and boost food security in SSA and it is largely agreed that this agricultural intensification must come with environmental sustainability. The will to support agricultural intensification with environmental sustainability especially in rural SSA was shown by the commitment of African heads of states in Abuja 2006 (Andriesse & Giller, 2015). As a result, agricultural intensification of food production systems has been receiving much attention and support. When this study was initiated, there was immense debate over sustainable intensification, its suitability, applicability, sustainability and how it was different from the business as usual agricultural practices from conventional intensification more largely promoted at that time. Several research and development activities were building evidence on the suitability and sustainability of different sustainable intensification practices, with sporadic outcomes and continued debate. Standing on the evidence produced in this work. I discuss the suitability, applicability, and sustainability of ecological intensification in the larger debate, leading to a better understanding of how ecological intensification could help smallholder farmers to sufficiently improve food production systems and concurrently ensure environmental sustainability in the face of climate change.

### 6.4.1 Suitability of ecological intensification for smallholder farming systems

In this thesis, I engage through critically examining issues concerning ecological intensification. I advance that ecological intensification is more clearly defined than sustainable intensification, with a better theoretical basis and particularly suits African smallholder farmers who operate under harsh environmental conditions with limited external inputs resources (Chapter 2). Ecological intensification aims to complement and (partially) replaces the limited non-renewable external inputs such as agrochemicals and inorganic fertilisers with production-supporting ecological processes, interactions and organisms in the long run. This ability of ecological intensification to increase productivity by complementing and or partially replacing the limited non-renewable external input resources makes it highly fit for smallholder farmers in SSA as they are operating under a harsh biophysical and socioeconomic environment with limited technical and financial resources.

In chapter 3 and 5, I give a full picture of the diverse smallholder farms in terms of input resources. This exposes the low input nature of smallholder agricultural systems. I argue that the low input nature of smallholder agricultural systems makes ecological intensification a better fit, due to its alignment to existing capacities, as well as in responding to the immediate need for improvement. I continue exploring how ecological intensification options fit within the heterogeneous biophysical and socio-economic characteristics of smallholder agricultural systems and communities (Chapter 4). This exposes the pivotal role that ecological intensification might play in enhancing soil fertility, soil and water conservation, pest suppression, productivity and imparts stability in resource constrained smallholder agroecosystems. This ability to address challenges and constraints of smallholder farmers' cropping system without substantial financial investments especially on external inputs clearly confirms its suitability as an intensification approach. In chapter 5, I reveal the large yield gaps in heterogeneous smallholder agricultural systems. This reveals the opportunity to improve yields at field level through intensification and ultimately improve food security. I show that integrating agroecological practices in current maize-based cropping systems can close the wide yield gaps, intensify production and simultaneously ensure environmental sustainability by significantly lowering GHG emissions in smallholder agriculture. I argue that this ability to increase yields substantially without substantial investment in external inputs makes it a highly suited intensification paradigm for smallholder agricultural systems, particularly for those smallholder farmers associated with poor resource profiles, low crop yields and environmental degradation.

### 6.4.2 Applicability of ecological intensification for smallholder farming systems.

Much research on agricultural intensification options has focused on the productivity potential, building scientific and technical evidence of increased production value, with little effort on how agricultural intensification options could be accepted and used within the broader biophysical and socio-economic context of heterogeneous farming systems and communities. Most agricultural development studies consider SSA to be homogenous do not account for farm type level differences such as production objectives, resource endowments and socio-economic aspects. Those are contextualised in this study, allowing to acknowledge smallholder farmers' circumstances, social views, perception of their realities and the management strategies used to meet their food requirements and income generation goals.

In Chapter 2, ecological intensification is regarded as a nature-based alternative that takes different forms and factors in local innovation to complement and/or partially replace external inputs, such as inorganic fertiliser, with production-supporting ecological processes, to sustain agricultural production while minimising adverse effects on the environment. This ability of ecological intensification to take different forms and factor in local innovation makes it highly applicable for the heterogeneous SSA smallholder farmers as they are not only an integral part of the innovation system but a valuable source of the innovation process. Ecological intensification achieves this by harnessing and exploiting ecosystem services. Chapter 3 confirmed that smallholder agriculture still more largely relies on ecosystem services rather than external inputs. Yet those ecosystem services have not been fully exploited and have a larger role to play in the agricultural intensification of food production systems in smallholder agriculture in SSA. A mastery by smallholder farmers of the supportive and regulatory ecological mechanisms, would support the full exploitation of ecosystem services and functions and consequently boost crop yields and improve food production systems. This can be achieved through ecological intensification which by nature is more applicable to smallholder farmers considering their resource limitations (Chapter 3).

In chapter 4, this thesis applied the UTAUT framework to assess how ecological intensification fit within the wider socio-economic context of smallholder farmers. The UTAUT framework clarified the diverse socio-economic factors that limit the applicability of these options in different smallholder farm types. The study provided evidence that (i) productivity potential alone does not enable acceptance and use of promising intensification technologies, (ii) other factors such as livelihood strategies, ease of use, social influence or enabling actors also have a large influence in enabling acceptance and use of those technologies and (iii) linking productivity potential, farmer priorities and how these intensification options apply in the wider livelihood and socio-economic context is key in enabling acceptance and use. Thus, working towards best-fit agricultural intensification options requires that options or practices be evaluated in a larger societal setting, together with stakeholders. The process must be negotiated, resulting in agreed concerns, priorities, values and trade-offs amongst stakeholders and with stakeholder institutions.

Building up from the heterogeneity (Chapter 3) and the need to enable acceptance and use (Chapter 4), I introduced a biophysical modelling approach encompassing a farm typology, crop modelling and farm focused GHG calculator to show the applicability of ecological intensification in maize based cropping systems. By integrating agroecological practices of conservation agriculture (CA) namely no till, residue retention and cover crops alone or in combination in current maize-based cropping systems, I showed the ability of these practices to raise productivity and ensure environmental sustainability through the reduction in GHG emissions. Additionally, these measures come without any substantial increase or investments in external inputs such as fertiliser, further ascertaining the applicability of ecological intensification to resource constrained smallholder agricultural systems and communities.

### 6.4.3 Ensuring environmental sustainability through ecological intensification in smallholder agricultural systems.

It is increasingly recognised and agreed that agricultural intensification must come together with environmental sustainability. Due to continuous land use and poor land management, environmental sustainability has largely been overlooked in smallholder agricultural systems. While several studies have focused on the productivity potential of agricultural intensification options, only a few studies have tried assessing the environmental sustainability aspects, particularly at the farm level in a smallholder context. Environmental indicators such as biodiversity and GHG emissions are essential in assessing environmental sustainability. Assessing these indicators is necessary to achieve the immediate need for increasing agricultural productivity as well as long term environmental sustainability. This thesis focuses on farm type level for sustainability assessments to provide practical information relevant for adapted, acceptable and usable for agricultural policy formulation.

Ensuring environmental sustainability means maintaining the natural resource base throughout for future generations. Several studies have exposed the rapid decline in the natural resource capital base of smallholder farming communities due to land and environmental degradation. Reversing these current trends of environmental degradation requires rehabilitation and restoration of ecosystem services and functions at the farm level. Smart and efficient use of natural functionalities and ecosystem services is imperative. In chapter 2, I highlight the need for long-term sustainability and argue that through ecological intensification, restoration of biodiversity, ecosystem services and functions of beneficial biological interactions, processes and organisms can be achieved and help rebuild our natural capital base to ensure long term environmental sustainability. Ecological intensification seeks to rehabilitate degraded agroecosystems, restore biodiversity and restore smallholder farming systems natural capital resource base. In Chapter 3, I argue that identifying and properly incorporating these ecosystems services and functions into smallholder farming will ensure environmental sustainability through natural capital build up rather than risking loss through the use of external inputs. Soils play a crucial role in meeting this vision for the future generations. For instance, improving sustainability in smallholder agricultural systems largely depends on maintaining and improving soil health, quality and fertility, which enables soils to sustain biological productivity, environmental quality and promote crop productivity. In chapter 4, I provide evidence that it is possible to ensure sustainability, especially of soils that have gone through serious nutrient mining and degradation. I show through farmers' acknowledgement that it is possible to improve soil fertility, soil conservation and reverse degradation through ecological intensification technologies without a large increment in the use of external inputs.

In chapter 5, I provide evidence that ecological intensification offers a win-win situation in terms of productivity and environmental sustainability, including where those could seem incompatible and contradictory. The results showed that current smallholder farms were relatively inefficient and unsustainable with low crop yields and high GHG emissions. Integration of agroecological practices into cropping systems proved to benefit both agriculture and the environment by providing ecosystem services that ensured improved productivity through increased yields and environmental sustainability through ecosystem services for climate regulation through mitigation of GHG emissions from cropping systems. I consequently argue that redesigning smallholder maize-based cropping systems based on the concept of ecological intensification can help ensure smallholder farmers achieve the twin objectives of improving productivity and ensuring environmental sustainability on their current land.

## 6.5 Concluding remarks

This thesis showed how highly valuable ecological intensification can be to improve food production systems and ultimately food security for smallholder farmers in SSA. This thesis presents evidence on the suitability and applicability of ecological intensification to contribute to improving food production systems, adapt and mitigate climate change and ensure environmental sustainability in the biophysically and socio-economically heterogeneous circumstances of rural SSA. The thesis argues and provides evidence that focusing intensification of smallholder agriculture through increasing use of inorganic fertilisers and agrochemicals is not the sole alternative. Increasing resource use efficiency through ecological intensification is an alternative, particularly for resource constrained farmers who rely mostly on ecosystem services for increased food production. The lack of consideration heterogeneous nature of the biophysical and socio-economic circumstances of smallholder farmers in SSA has led to many flaws in agricultural development programs and agricultural intensification in SSA. As a result, Africa still lags behind the rest of the world in terms of food security, despite its potential to become a major food producing continent. This thesis recognises that transitioning towards successful acceptance, use and scaling of ecological intensification requires new sources of knowledge, methods, more transparent and better analysis of synergies and trade-offs in the heterogeneous biophysical and socio-economic context of smallholder farmers. Therefore, this study encourages revisiting smallholder agricultural intensification policies and research through a clearer appreciation of diversity for immediate production increases and revitalisation and sustainability of natural resource capital. Agricultural research scientists, ecologist, extension officers, government bodies and private sectors must be encouraged to engage with smallholder farming communities, to co-learn and co-explore the alternatives which address specific agroecological and socio-economic conditions and smallholder farmers preferences. In doing so, research on agricultural intensification will acknowledge better the real complex relationship between farmland and nature, between smallholder farmers and their farmland and become more relevant to those food production systems which have a large potential for increase and ultimately impact food security at large.

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