It's time to harvest!

Towards sustainable farming systems in the East African highlands

Wytze Marinus

Propositions

1. Land and capital limit smallholder farmers' incomes in sub-Saharan Africa (SSA), not technology.
   (this thesis)
2. Changes required for future farming systems need to be tested at farm level.
   (this thesis)
3. Education and training of field assistants is more important for good quality data than developing smart survey apps.
4. Cooperation and co-learning with local partners, from field assistants up to professors, should be considered as important as the scientific outcomes of research projects in SSA.
5. Governments calling farmers with low productivity "not serious", do not take their farmers serious.
6. Social media make us less social.

Propositions belonging to the thesis, entitled
It's time to harvest! Towards sustainable farming systems in the East African highlands

Wytze Marinus

Wageningen, 8 December 2021

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Abstract

The UN Sustainable Development Goals of *Zero poverty* and *Zero hunger* include *leaving no one behind* as a key principle. However, many smallholder farmers in sub-Saharan Africa (SSA) are caught in a poverty trap, a vicious cycle of low productivity and limited ability to invest. Moreover, small farm areas may limit the potential benefits that can be accrued at farm level, even if productivity would increase. Sustainable intensification is a key strategy to increase agricultural production for the growing population in SSA, while at the same time avoiding the extension of agricultural land in natural areas. In the first part of the thesis I used an 'impact-oriented' perspective to assess, within current farming systems, to what extent integrated co-learning leads to sustainable intensification. In the second part I used a 'target-oriented' perspective to explore 'viable farm sizes' required to attain a living income (the income required for a decent living including a nutritious diet, clothes, schooling and housing). By situating this study in the East African highlands, characterized by high population density and small farm sizes, I revealed possible pathways towards more sustainable farming systems.

We developed the 'integrated co-learning approach', which combines input vouchers with iterative learning cycles on sustainable intensification, and tested it in western Kenya from an impact oriented perspective. Farmers participating in co-learning had a more diverse and cohesive knowledge after five seasons compared to farmers who only received the voucher. Irrespectively of the co-learning, the voucher immediately increased farm level maize yield from less than 20% to 40-50% of water-limited yield. This indicates that closing yield gaps is mainly limited by capital constraints and not by technology or knowledge. However, co-learning facilitated the more complex changes in the cropping system that are required for sustainable intensification, such as the incorporation of legumes.

Although yields improved after the introduction of the voucher, the value of produce from crops was still below the living income benchmark for most households due to their small farm areas. Increasing yield alone was thus not enough to attain a living income from arable farming. Also for other indicators of sustainable intensification the desired outcomes were often not achieved. For instance, nitrogen (N) use efficiency remained too high, indicating the risk of soil N mining. Maize area and farm area also increased, all pointing towards the pathway of extensification instead of desired intensification. This implies the need for policies that favour increased input use and policies that limit area expansion.

Building on the finding that farm size strongly limited farmer income, we explored viable farm sizes for contrasting future scenarios in three sites in the East African highlands. This target-oriented perspective revealed that in the current baseline scenario, cultivated areas per farm would have to increase by 4.5, 1.3 and 2.5 times in Nyando (Kenya), Rakai (Uganda) and Lushoto (Tanzania) respectively, to make a living income. However, if crop yields increased to 50% of the water-limited yields, current cultivated areas of most households (>70%) would be large enough to make a living income in Rakai and Lushoto. In Nyando additional sources

of income, such as income from livestock, were required to make a living income.

Comparing the outcomes of the two different perspectives indicates that increasing yields of staple crops, e.g. through input subsidies, is not enough for all farmers to make a living income from current farm sizes. Larger changes are required, both within the farming system, e.g. increasing farm areas and/or cultivating more profitable crops, as well as outside the farming system, e.g. alternative employment options outside agriculture. The integrated co-learning approach can be deployed to explore incentives for smallholder farmers to sustainably intensify. Further research is required on how to scale the approach and integrate it into extension systems while keeping the valuable farm-researcher feedback. The viable farm size as a benchmark is a useful method for assessing how to *leave no one behind* while moving towards more sustainable farming systems.

Contents

Chapter 1

General introduction

1.1 The need for more sustainable farming systems in the East African highlands

The United Nations Sustainable Development Goals (SDGs) have set ambitious targets – i.e. SDG 1 Zero Hunger, SDG 1 No Poverty – by 2030 (United Nations- Economic and Social Council, 2016). One of the key underlying principles of the SDG's is *leaving no one behind*. This may in particular be a challenge in sub-Saharan Africa (SSA), as the population is expected to double by 2050 (UN-DESA, 2019). Moreover, more than two-third of the world's poor currently work in agriculture (Olinto et al., 2013), making agriculture key in rural livelihoods (Dercon and Gollin, 2014; Diao et al., 2010). The increasing population density is a particularly strong challenge in the East African highlands as it is among the highest in SSA (The World Bank, 2021a). Due to this population pressure, land scarcity is high in the East African highlands, resulting in the smallest average farm sizes on the continent (Jayne et al., 2014), limiting the potential income that can be accrued from a farm, even if yields would increase (Gassner et al., 2019; Harris and Orr, 2014). These small farm sizes, together with constraints such as limited market access and a changing climate, ask for considerable changes in current farming systems (Giller, 2020). At the same time, increases in agricultural production have to keep pace with the food demands of the growing population and to achieve food self-sufficiency and national and regional level (Jayne and Sanchez, 2021; Thornton et al., 2018; van Ittersum et al., 2016). Current crop yields, however, are low and to reach food self-sufficiency in 2050 at national or regional level, unprecedented yield increases would be required (van Ittersum et al., 2016). This provides a huge challenge if we focus on the smallholder farming community: how can rural livelihoods be improved while increasing agricultural production and *leaving no one behind*?

1.2 The poverty trap at farm level limits current yield increases

Many smallholder farmers in SSA are caught in a poverty trap, a vicious cycle of low productivity and lack of opportunities and incentives to invest in agricultural inputs (Koning, 2017; Tittonell and Giller, 2013). Low agricultural productivity in SSA is often caused by a combination of poor soils (Sanchez, 2002) and low input use (Headey and Jayne, 2014a). The heterogeneity in soil fertility as a result of the poverty trap, both between and within farms (Tittonell et al., 2005b, 2005a; Zingore et al., 2007a), further compounds the challenge of increasing yields (Tittonell and Giller, 2013). Fields that are low in soil fertility tend to be found with poorer farmers, limiting their opportunities to increase yield (Franke et al., 2019; Vanlauwe et al., 2006; Zingore et al., 2007b). The commonly deep and well drained soils in the East African highlands, however, generally show good response to mineral fertilizers (Njoroge et al., 2017; Vanlauwe et al., 2006). Also across SSA, fertiliser use tends to be profitable, while its use is low (Nin-Pratt, 2016). This low use can be the result of the low financial capacity that many smallholder farmers have (Duflo et al., 2011), hence the limiting investment in inputs such as fertiliser. Moreover, due to the previously mentioned heterogeneity, it is unknown if yields can increase for most farmers at farm level, as there are limited empirical examples at farm level (e.g. Sanchez et al., 2007). Farm level yield increases, however, will be essential for the required yield increases at national level, which in turn requires an understanding of how these yield increases can be attained and what will be required to overcome the poverty trap.

Small farm sizes make this poverty trap a double poverty trap as farmers may not only be in this current vicious cycle of low productivity, but are also limited by their farm area to have substantial benefits if productivity would increase (Giller et al., 2021). Current household welfare is linked to farm size (Frelat et al., 2016). The limited potential benefits that can be argued at farm level have been shown both from larger studies across multiple countries (Gassner et al., 2019; Giller et al., 2021; Harris and Orr, 2014) as well as more detailed work based on farm typologies in a country or region (e.g. Falconnier et al., 2018; Leonardo et al., 2018). These limited potential gains at farm level are also one of the reasons why farmers currently invest little in inputs for their farms. Most of the current studies that assessed the potential gains at farm level have used survey data and modelled possible yield and income increases. Little empirical research has been done, however, to assess to what extent household income from farming would increase if productivity increases and how this differs for households with different farm sizes.

1.3 Sustainable intensification to improve livelihoods?

Historically, increasing agricultural production led to negative side effects. Overuse of manure and other inputs for instance became an issue in the 1970s and 1980s in Europe as it led to environmental pollution (e.g Sutton et al., 2011). Also in emerging economies, e.g. in South-East Asia and China, similar problems occurred when cropping systems intensified and Nitrogen (N) use increased (Zhang et al., 2015). In SSA, increased agricultural production has mainly come from expanding crop land instead of intensified production (Giller et al., 2021; Jayne and Sanchez, 2021), which leads to increased pressure on important natural ecosystems (Baudron and Giller, 2014). 'Sustainable intensification' has therefore been proposed as a new paradigm for agricultural production, both for highly intensified systems, e.g. in Europe and the United States (e.g. Rockström et al., 2016; Tilman et al., 2011, 2002), as well as for less intensified smallholder farming systems in SSA (e.g. Pretty et al., 2011; The Montpellier Panel, 2013; Vanlauwe et al., 2014). Sustainable intensification aims to enhance production per unit land, nutrient and labour input, while reducing environmental damage, building resilience and natural capital, and securing environmental services (e.g. Pretty et al., 2011; The Montpellier Panel, 2013).

Research on sustainable intensification, however, has been criticised for having a too narrow focus, on increasing yields and improving economic performance (Godfray, 2015; Struik et al., 2014; Struik and Kuyper, 2017). This resulted in alternative concepts such as ecological intensification (Tittonell, 2014). Another limitation that is often noted is the limited attention for social sustainability (Loos et al., 2014; Smith et al., 2017). Struik and Kuyper (2017) argue that indeed multiple dimensions of sustainability should be included and that the concept of sustainable intensification can be used as a “process of inquiry and analysis”. As food demand increases with the growing population, such a process of inquiry and analysis can be used to assess how agricultural production can meet this demand and which trade-offs emerge. Using a diverse set of indicators to describe these trade-offs can inform decision making by society and policy makers (Struik et al., 2014; Struik and Kuyper, 2017). Such an analysis may also help to prioritize goals and identify key limitations, such as the poverty trap, to sustainably increase productivity in SSA.

1.4 Incentivizing yield and income increases

Incentives are needed to overcome current constraints for sustainable intensification of smallholder agriculture. This could include input subsidies, which have become more popular again in SSA in the past two decades (Jayne et al., 2018) and/or a wider set of incentives with measures such as price subsidies, price protection and/or land reforms (Koning, 2017; Wiggins, 2016). The increased attention to input subsidies came after decades of low government investments in the agricultural sector. With the structural adjustments in the 1980s and 1990s many governments were pushed by the World Bank and others to cut budgets and to reduce subsidies and other government support to the agricultural sector (Koning, 2017). Growing concerns however on population growth and the need for national food self-sufficiency led for instance the Malawi government and donors to reinstall fertiliser and seed subsidies in 2006 (Chirwa and Dorward, 2012; Jayne et al., 2018). Also other countries reinstalled input subsidies, e.g. Ghana, Nigeria, Zambia and Kenya (Jayne et al., 2018). Apart from increasing yields, increasing smallholder incomes is a key goal of such subsidies (Jayne et al., 2018).

Input subsidies can thus be part of the measures to overcome the poverty trap. Using such inputs, requires new knowledge on effective application. Dorward et al. (2008) for instance pointed to the limited extension services that came with the Malawi fertilizer programme, as a possible reason for the low N use efficiencies by participating farmers. Government extension services in SSA however, reduced considerably with the structural adjustments, as for instance described in detail for Kenya by Poulton and Kanyinga (2014). New tools and approaches for extension may thus be required if production is to increase through incentives such as input subsidies.

1.5 Farming systems analysis to assess opportunities and constraints for sustainable intensification

Farming systems analysis consists of a range of tools and methods that can be used to assess the performance and to design new options at farm and farming systems level. It uses methods like co-learning, detailed farm characterization, trade-off analysis and benchmarking to develop new options that can fit the heterogeneity of smallholder farming systems (Descheemaeker et al., 2019). Farming systems analysis can thereby be key in developing more sustainably intensified farming systems.

1.5.1 Co-learning on increasing farm level production

Co-learning emphasizes the advantages of learning by farmers and facilitators together (Röling, 2002). As part of an iterative framework, co-learning can be a useful method to develop the localized knowledge that is required for sustainable intensification (Descheemaeker et al., 2019). Ronner et al. (2019) for instance showed how co-learning can lead to a diverse set of options for climbing bean cropping systems that fit the diverse needs of farmers in an area. Falconnier et al. (2016) showed that outcomes from co-learning activities could be used to explain variability in yield responses. Few studies however have focussed on co-learning to increase production at farm level. Modelling studies have shown that considering interactions at farm level can be key for improving productivity and farmer income (e.g. Tittonell et al., 2009; Van Wijk et al., 2009). Although many of these modelling studies started with a detailed characterization of the farming system to inform their modelling work (e.g. see Tittonell, 2008, Figure 4.), little empirical work has been done to assess whether these farm level interactions indeed could lead to production increases. Dogliotti et al. (2014) and Falconnier et al. (2017) are positive exceptions. Dogliotti et al. (2014) describe two to five years of interactions between farmers and researchers leading to positive changes in farm management and income increases of vegetable farmers in Uruguay. Falconnier et al. (2017) describe how two cycles of co-learning over three years allowed the design of cropping systems that fitted specific soil fertility niches and increased farmer income, while maintaining food self-sufficiency. Both studies, however, worked within current farming systems and did not specifically consider incentives to overcome the poverty trap and increase input use. This often leads to limited options and benefits for low resource endowed farms (e.g. Falconnier et al., 2017; Ronner et al., 2019) and limits the so called 'solution space' for improvements in the farming system (Martin et al., 2013). Input subsidies or vouchers could be used to increase the solution space, also for the poorer households in a community. Little is known, however, on to what extent co-learning activities on increasing whole farm production can lead to changes in farmers' decisions and management and whether this can lead to sustainably intensified farming systems.

1.5.2 Indicators and benchmarks for assessing systems performance

Indicators and their benchmarks can be used to measure systems performance towards sustainable intensification. A multi-criteria assessment of indicators associated with the principles of sustainability can thereby help to assess the multiple goals of sustainable intensification. Using a framework of principles and criteria warrants transparency and a justified selection of indicators (Florin et al., 2012). According to Florin et al. (2012, p.109), "*Principles are the overarching ('universal') attributes of a system. Criteria are the rules that govern judgement on outcomes from the system and indicators are variables that assess or measure compliance with criteria*". Criteria can also help to decide upon benchmarks to judge whether a goal is reached. Within sustainable intensification of smallholder farming systems, criteria, indicators and benchmarks need to address different levels, including the field, farm and household level. At national level, increasing yields to a certain threshold is required to attain food self-sufficiency, while at farm level maize self-sufficiency and household income are important indicators that fit farmers' objectives.

A commonly used benchmark for household income in developing countries is the poverty line, which considers the minimum cost for making a living in the world's poorest countries (Chen and Ravallion, 2010; Ravallion et al., 1991). This benchmark, however, is not site specific and does not consider the requirements for a *decent* living as considered in the human rights that were declared in the United Nations General Assembly (1948) (van de Ven et al., 2020). The 'living income' has therefore been developed as an additional benchmark that is based on the human rights and considers the income required for a nutritious diet, housing, education and healthcare (Anker and Anker, 2017a; van de Ven et al., 2020). The living income so far has been used to benchmark incomes in commodity crops such as tea (Anker and Anker, 2014), cocoa (Smith and Sarpong, 2018) and flowers (Anker and Anker, 2017b). Van de Ven et al., (2020) recently adapted the methodology for application in smallholder farming systems that are more focussed on staple crops. This allows benchmarking of current farmer incomes against the living income as was done by Giller et al. (2021), using large scale survey data. So far, however, this has not yet been done using measured farm level data that can give a detailed insight into farm or household level opportunities and constraints. Using the living income as a benchmark may also result in the question what farm area is required to attain a living income, as was previously done using the poverty line (Gassner et al., 2019; Harris and Orr, 2014).

1.6 Study objectives

From the above I summarise that sustainable intensification of smallholder farming systems is required for the necessary yield increases in SSA. Many smallholder farmers, however, are currently poor, so that financial incentives have a high potential to increase input use and thereby yields. Little is known however on whether such incentives can lead to farm level yield increases or whether additional constraints currently limit these yield increases, such as low soil fertility, small farm sizes and lack of knowledge. Furthermore, with yield increases, other indicators for sustainable intensification will be affected over time, thus influencing the pathways for sustainable intensification. Assessing these pathways can also reveal further constraints and opportunities for sustainable intensification of smallholder farming systems. Current farm area may be a key constraint for household income and it is unknown what farm area will be required to attain a living income from farming. This led to the following main objectives, which link to the four research chapters of this thesis:

1) To develop and test an integrated co-learning approach for whole-farm sustainable intensification (Chapter 2),

2) To assess to what extent increasing yields can provide a living income from smallholder farming (Chapter 3),

3) To assess how the integrated co-learning approach influenced pathways of sustainable intensification (Chapter 4),

4) To assess the farm area required to make a living income from smallholder farming in future farming systems (Chapter 5).

1.7 Study area

This study took place in the East African highlands. The East African highlands can be characterized by relatively good rainfall and bi-modal cropping seasons. Together with the generally deep and well-drained soils, this results in relatively good agronomic potential (Vanlauwe et al., 2013). The population densities in the East African highlands, however, are among the highest in SSA (Vanlauwe et al., 2013), also resulting in average farm sizes that are among the smallest in SSA (Headey and Jayne, 2014a). With growing populations across SSA (UN-DESA, 2019), current population densities, small farm sizes and other agricultural developments in the East African highlands may give an insight in future agricultural developments for other areas in SSA. At the same time, studying options to sustainably increase agricultural production is of key importance for the East African highlands itself. Due to continuing population growth, even with production increases it may be difficult to attain national food self-sufficiency for important staple crops in future (van Ittersum et al., 2016). For Chapters 2 to 4 we selected western Kenya, as much research was done in this area previously, which forms a useful source of knowledge for the co-learning activities. Two sites with contrasting population densities were selected, Vihiga and Busia, with 1050 people km^{-2} and 530 people km^{-2}, respectively (KNBS, 2019). Average farm size was smaller in Vihiga, <0.5 ha, than in Busia, about 1.0 ha (Jaetzold et al., 2005).

1.8 Thesis outline and research methods

This thesis uses two contrasting perspectives as shown in Figure 1.1. Chapters 2 to 4 use an 'impact-oriented' perspective with the aim of increasing farm level production (in kg produce and/or USD) through sustainable intensification within current farming systems. Chapter 5 uses a 'target-oriented' perspective by setting the living income as a target and assessing the farm area required to attain a living income in possible future farming systems.

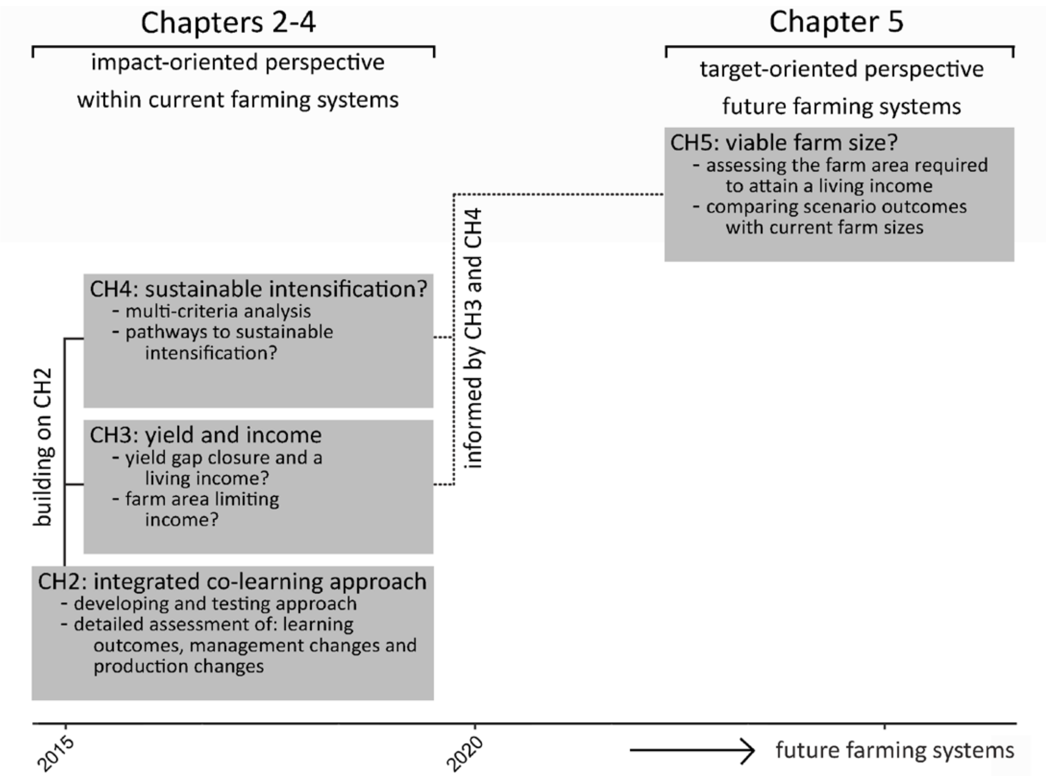

Fig. 1.1: An overview of how the assessments in Chapters 2 to 4 and Chapter 5 relate to current and future farming systems. In Chapters 2 to 4 yield increases were assessed within current farming systems as part of the integrated co-learning programme, which included a US$ 100 input voucher per season. In Chapter 5 scenario analyses were done with different yield levels to assess the farm area required to obtain a living income.

In Chapter 2 I present and test the 'integrated co-learning approach', which is comprised of four complementary elements: input vouchers, an iterative learning process, common grounds for communication, and complementary knowledge. The approach was tested over five seasons by differentiating a group of comparison farmers, who only received the USD 100 input voucher per season, and a group of co-learning farmers who also took part in the co-learning activities. Each cropping season was considered a learning loop, starting with a co-learning workshop before the cropping season, followed by farm monitoring and yield sampling visits during the season and ending with a seasonal evaluation interview before the next workshop. The data collected as part of these activities was also used in Chapters 3 and 4. In Chapter 3 I assessed the change in yield and crop value of produce (as an estimate for income) due to the input voucher, by comparing value of produce before and during the voucher programme. I use the 50% of the water-limited yield as a benchmark for yield and the living income as a benchmark for value of produce. Moreover, I relate the value of produce to farm area to assess to what extent farm area limits value of produce. In Chapter 4 I conduct a multi-criteria analysis using the five seasons of farm level data. Analysing indicator outcomes over multiple seasons also allows for identifying possible pathways towards sustainable intensification. In Chapter 5 I present the 'viable farm size' concept: i.e. the farm area that is required to attain a living income. I use survey data from three contrasting sites in the East African highlands – Nyando (Kenya), Rakai (Uganda) and Lushoto (Tanzania) – to explore viable farm sizes in six scenarios. Starting from the baseline cropping system, I build scenarios by incrementally including intensified and re-configured cropping systems, income from livestock and off-farm sources. These viable farm sizes are then compared with the distributions of current farm sizes from the survey data. I end this thesis with the general discussion (Chapter 6) in which I compare the outcomes of the impact-oriented and target-oriented perspectives, and highlight how the outcomes of this thesis can be used in future research.

"That is my farm" – An integrated co-learning approach for whole-farm sustainable intensification in smallholder farming

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Abstract

The use of options for sustainable intensification of smallholder farming in sub-Saharan Africa is often limited by knowledge and resource constraints. To address both constraints, we developed and tested an integrated co-learning approach to improve farm level productivity. The approach was tested by differentiating a group of co-learning farmers and a group of comparison farmers in two locations in western Kenya during five seasons. Both groups received a USD 100 voucher each growing season and the co-learning group also took part in co-learning activities. The integrated co-learning approach was comprised of four complementary elements: input vouchers, an iterative learning process, common grounds for communication, and complementary knowledge. Central to the approach were co-learning workshops before each season. Workshop topics built on topics from previous seasons and on farmers' feedback and researchers' observations. Activities during each season included farm management monitoring, yield measurements and evaluation interviews. This resulted in multiple learning loops for both farmers and researchers. The voucher fostered learning through increased and diversified input use. For instance, intercropped legumes were smothered by the prolific growth of maize resulting from increased fertilizer use. After setting up joint demonstrations, farmers started to use alternative spacing options for intercropping. Building common ground on concepts and processes governing farm system functioning fostered a deeper understanding by farmers on the suitability of options to their farm and by researchers on locally relevant content. Soil fertility gradients was such a concept through which judicious use of fertilizers was discussed. After five seasons, co-learning farmers had a more diverse and cohesive knowledge of their farm than comparison farmers. Co-learning farmers highlighted farm level management options, management of the parasitic weed striga and options for integrated soil fertility management as the most important things they learned. A tangible learning outcome was the continued increase in groundnut and soybean area among co-learning farmers, which led to more diversified maize cropping systems. We attribute these differences to the co-learning process. Our results demonstrate how the integrated co-learning approach changed both knowledge and practices of participating farmers and researchers. The amplifying effects of the four key elements appeared to be important for enabling sustainable intensification of smallholder farming systems.

Keywords:

input vouchers, subsidies, extension services, iterative cycles, knowledge, farming systems analysis

2.1 Introduction

Sustainable intensification of smallholder agriculture is seen as a key pathway to lift smallholder farmers from poverty and to feed the growing population of sub-Saharan Africa (SSA) (e.g. Pretty 2011; The Montpellier Panel 2013; Vanlauwe et al. 2014). It aims to enhance productivity per unit land, nutrient and labour, while reducing environmental damage, building resilience and natural capital, and securing the flow of environmental services (e.g. Pretty et al., 2011; The Montpellier Panel, 2013). However, many management options for sustainable intensification are knowledge intensive and require expensive external inputs, making them out of reach for many smallholder farmers. Moreover, riskiness, labour shortage and limited benefits that can be accrued from small farms reduce the adoption potential of sustainable intensification options for smallholder farmers (Giller, 2020; Hazell et al., 2010; Wortmann et al., 2020). Hence, for a large part of the population, livelihood improvement through sustainable intensification is beyond reach (e.g. Falconnier et al. 2018; Leonardo et al. 2018; Ibrahim et al. 2019; Silva et al. 2019). Many of the above-mentioned constraints are intertwined, e.g. lack of capital reduces the need for knowledge on new options, resulting again in little need to avail this knowledge to farmers (Tittonell and Giller, 2013). A combination of structural changes such as input subsidies, land reforms, mechanisation and/or knowledge transfer programs may therefore be needed to make sustainable intensification a feasible pathway for smallholder agriculture.

With the growing population and expected production challenges induced by e.g. poor soils and climate change in SSA (van Ittersum et al., 2016), input subsidies gained renewed attention (Jayne et al., 2018). Support mechanisms such as input subsidies, product price subsidies and extension services in SSA were severely reduced in the 1990s and further deteriorated through poor policies and their implementation (e.g. Poulton and Kanyinga, 2014). Experience in Africa has shown that subsidies (Jayne et al., 2018) or relatively small incentives through nudging (Duflo et al., 2011) can increase input use of smallholders. In Malawi, however, limited impact of increased input use on crop yields was observed, possibly because little advice was given on how to manage the subsidised inputs effectively (Dorward et al., 2008b). In other words, when capital constraints are partly alleviated knowledge may become limiting and learning on implementation of new options becomes necessary.

The aim of input subsidies is generally to increase both household and regional level agricultural production, through the increased use of inputs, such as certified seed and mineral fertilizers, often focusing on staple crops such as maize. This focus on staple crops neglects crop diversity, while other crops such as legumes can play an important role in sustainable intensification (Vanlauwe et al., 2014, 2019). Including a larger set of inputs and crops may therefore be useful (Mungai et al., 2016). However, little is known on the type of knowledge required when such a range of farm inputs is included in a subsidy scheme. Which options for sustainable intensification become relevant, for whom, under which conditions, and how can farmers acquire that knowledge? Many farmer learning programs, such as farmer field schools (Braun et al., 2006), focus on options for improvement within the current constraining conditions, as such limiting the 'solution space' (Martin et al., 2013). When reducing the capital constraints a mix of external and farmer knowledge and experience is required for selecting the best fit options. External knowledge, e.g. from research, can provide information about new options, but farmer knowledge is required to check for local relevance and feasibility. Co-learning combines the two perspectives (Röling, 2002), and as part of an iterative learning framework, it facilitates the development of shared and contextualized knowledge (Descheemaeker et al., 2019). The inclusion of farmers in this process inherently includes evaluation from a farm level perspective, the level at which decisions are made (Giller et al., 2006). However, few studies that consider changes at the farm level, include iterative learning with farmers, with some exceptions. Dogliotti et al. (2014) show how multiple seasons of co-innovation led to considerable changes in farm management. Falconnier et al. (2017) describe how combining farmers' and researchers' knowledge and experiences helped them in understanding the diversity of responses to different options. Interactive learning about improving farm management requires methods to communicate between farmers and researchers. Farmers and researchers may understand the farming system in different ways, while shared understanding is needed for effective discussions (Joshua J. Ramisch, 2014; van Paassen et al., 2011). Visual tools, such as resource flow maps, can help in discussing abstract concepts, like nutrient flows on a farm (Defoer et al., 1998). However, developing a shared understanding takes time and requires iterations.

The above motivated us to develop an *integrated co-learning approach* that aims to increase whole farm production of smallholder farmers through sustainable intensification. We refer to this as an integrated approach as it combines input subsidies through an input voucher with iterative learning cycles, communication methods between farmers and researchers and knowledge of both farmers and researchers. The input voucher is a structural component to enable increased input use. Our work was driven by the following objectives: (i) to develop an integrated co-learning approach for farm-level sustainable intensification, (ii) to track and assess the learning outcomes over multiple seasons, (iii) to assess changes in farmer choices and practices. We thereby tested the following overall hypothesis: When resource constraints are partly alleviated, co-learning can be effective in changing both knowledge and practices of farmers and researchers.

2.2 Methodology

The integrated co-learning approach was developed over a period of five seasons. Theoretical understanding on learning informed the development of a range of activities, including co-learning workshops, farm monitoring, and farmer evaluation interviews. These were implemented in iterative cycles and enabled through input vouchers, alleviating resource constraints for farmers. The study took place in western Kenya where we could build on a wide range of earlier experimental and whole-farm modelling studies. We used the learning that took place around integrating legumes in maize based cropping systems and options to reduce incidence of the parasitic weed striga (*Striga hermonthica* (Delile) Benth.) to exemplify how the elements of the integrated approach facilitated learning. We first describe the theoretical grounding for the approach (sub-section 2.2.1) and the tools and data underpinning the co-learning workshops (sub-section 2.2.2). Sub-section 2.2.3 explains how the approach was tested.

2.2.1 Theoretical grounding

Co-learning emphasises the advantages of learning by farmers and facilitators together (Röling, 2002). Descheemaeker et al. (2019) describe how the iterative nature of co-learning cycles helps in adapting farming options to the diversity of local conditions. Learning of participants – farmers, field assistants, researchers – is central in such an approach. Following (Defoer, 2000), we see learning as the accumulation or reassessment of knowledge. The theory on *experiential learning* (Kolb 1984) inspired many to develop iterative learning based concepts, e.g. the DEED-cycle (Descheemaeker et al., 2019; Giller et al., 2008) and other decision making frameworks (e.g. Brown et al. 2005; McCown et al. 2009). Kolb's experiential learning cycle contains four stages: *concrete experience*, *reflective observation*, *abstract conceptualisation*, and *active experimentation*. An experience contributes to learning, according to Kolb, if it takes the learner through all four stages. We therefore explicitly included all four stages in our co-learning approach. Moreover, Kolb's definition of learning – "*learning is the process whereby knowledge is created through the transformation of experience*" (Kolb 1984, p. 41) – emphasizes the link between cognition and action (Loeber et al., 2007), which we implemented in our participatory (action) research (e.g. Defoer 2000).

Experiential learning does not consider the (social) context in which the learning takes place, nor does it consider the norms and values of the learners (Loeber et al., 2007). Following Argyris and Schön (1996), the importance of changing one's (or a group's) values and interests should be considered in learning. Loeber et al. (2007) refer to changing the '*theories-in-use*', being the underlying values, believes and theories of an individual or a group. An atmosphere of trust and continuity is needed for someone to dare question or discuss their theories-in-use, in particular in group activities (Duveskog et al., 2011; Grin and Hoppe, 1995). We covered this in our design by multiple seasonal meetings and activities that facilitated interaction among farmers and between farmers and researchers.

Leeuwis and Van den Ban (2004) emphasised the importance of quality feedback as part of learning cycles, resulting in a critical role for the facilitator (Loeber et al., 2007). Including new knowledge in such learning cycles is another key role of the facilitator (Ramisch et al., 2006). New knowledge will only be “well received” if it is relevant to and understandable by the learner (Carberry et al., 2002). Visualisation may be a useful tool to introduce new knowledge and communicate about the farming systems (Leeuwis and Van den Ban 2004). Simple visual diagrams were, for instance, used by others to communicate model results with farmers in Australia (Carberry et al., 2002), France (Duru and Martin-Clouaire, 2011) and in Zimbabwe (Carberry et al., 2004). We incorporated visualization for discussing the processes underlying the farm system functioning.

2.2.2 Case study

Integrated co-learning trajectories were initialised in two contrasting locations in western Kenya in August 2016, Vihiga and Busia, and continued for five seasons over two and a half years. Western Kenya has a bimodal rainfall pattern, with the ‘long rains’ from March to June and the ‘short rains’ from September to November. The agro-ecological and socio-ecological context differs between the two locations. Vihiga was a site with a very high population density, among the highest in rural SSA (>1000 people km^{-2}), which results in small farm sizes (< 0.5 ha per farm) and households being only food self-sufficient for part of the year. Farms in Busia are larger (1.0 ha per farm) and the population is less dense (450 people km^{-2}) (Jaetzold et al., 2005; KNBS, 2009; Tittonell et al., 2005a). A maize-legume cropping system is dominant in both locations. The low soil fertility is a major constraint to improving the currently poor yields. Maize self-sufficiency is the main objective for the majority of the farmers, although often not met (Crowley and Carter, 2000; Tittonell et al., 2005a). Moreover, striga strongly affects maize yields, in particular with low inputs and continuous maize cultivation (Jaetzold et al., 2005; Vanlauwe et al., 2008). Cows are important livestock in the area with local breeds used for traction (mainly in Busia) and dowry, while pure and cross-bred dairy breeds such as Friesian, Ayrshire or Guernsey are kept for milk production, in particularly by better-off households (Tittonell et al., 2005a).

A large initial farm survey was used to select smaller groups of farmers, for detailed analysis. In each location two sub-locations were selected, which were sufficiently apart to prevent knowledge exchange between groups. A ‘co-learning’ group of 12-13 farmers in one sub-location took part in the co-learning trajectory including workshops and advice (Fig. 2.1). The ‘comparison group’ in the other sub-location (n=13) did not take part in workshops and received no advice. Both groups received an input voucher each season of USD 100. The amount was based on the input-loan a new farmer could get from One Acre Fund (OAF), a social enterprise active in the area. Farmers who had repaid initial loans could get loans up to USD 272 (OAF, 2016). A voucher of USD 100 was therefore expected to alleviate part of the resource constraints, while not being extraordinarily large. The voucher could be exchanged for farm inputs which were distributed by the project. To select farmers representing the diversity in the area, we used the type and number of livestock owned as criteria. We classified them as farmers owning at least one dairy cow (>1 Tropical Livestock Unit, TLU, of a pure or cross-bred dairy breed); farms owning at least one local cow (>1 TLU) and no dairy cattle; farmers owning only a calf or no cattle at all (<1 TLU). Four households of each class participated in each group. Both the man and the woman in the household were invited to participate in the workshops and voucher handout.

2.2.3 External knowledge informing the workshops

Seasonal co-learning workshops served as key moments for knowledge transfer, discussion and feedback. The content introduced by the facilitators during these workshops focused on sustainably intensifying farm production expressed as physical yield or value of production. Sustainability inherently considers using production methods that can support current and future generations, meaning that both short and longer term benefits need to be considered (e.g. Zingore et al. 2011). Trade-offs and synergies of the options for different farm components, e.g. investing in crops or livestock, were therefore part of the workshop content. Workshop topics thereby built on the thinking of Integrated Soil Fertility Management (ISFM) (Vanlauwe et al., 2010) and used tools of farming systems analysis (Descheemaeker et al., 2019; Giller et al., 2011).

2.2.4 Assessing the integrated co-learning approach

We tested the approach as an integrated set of elements, not having the aim to test the effectiveness of the separate elements, following (Banerjee et al., 2015). A distinction was made between assessing the learning outcomes (Objective 2) and the farmer choices and practice changes (Objective 3). Learning outcomes were assessed by comparing differences between the comparison group (T_1) and the co-learning group (T_2, Fig. 2.1). This was done by monitoring the learning process through the seasonal evaluation interviews and observations during the workshops and through a final evaluation interview with the co-learning and

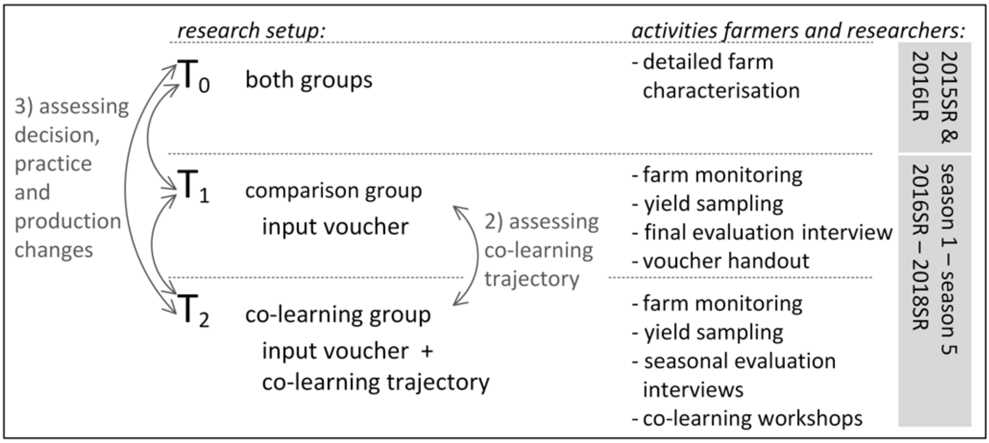

Fig. 2.1: Schematic overview of assessment of the effectiveness of the integrated co-learning approach. SR: short rains cropping season, LR: long rains cropping season.

comparison groups. Indicators of learning by farmers were recognition and active discussion about workshop topics and remembering these topics five to six months after the workshops. Learning by researchers was assessed through monitoring changes or evolution in workshop topics. Also, changes in the co-learning trajectory, e.g. in activities or sources of information were seen as learning by the researchers. Convergence or changes in theories-in-use, among farmers and between farmers and researchers, were additional indicators for success of the approach.

Farmer choices and practice changes were assessed by comparing the choices of inputs from the voucher and farm management between both groups during the project (T_1 and T_2) and by comparing farm management in the initial situation (T_0) with that during the project (T_1 and T_2). Co-learning farmers also filled in a preliminary voucher before the workshop to assess effects of the workshops on their choices. Practice changes were assessed based on the initial detailed farm characterisation and the farm monitoring. As we focused on legume cultivation, and its interactions with other farm components, indicators for practice changes were a change in the cultivated area and cultivation practices of legumes.

2.3 Results

2.3.1 The integrated co-learning approach

The integrated co-learning approach (Figure 2) resulted from a continuous process over five seasons. Four key elements played an important role: 1) *the input vouchers*, 2) *iterative cycles of activities*, 3) *common grounds for communication*, and 4) *complementary knowledge*. The four elements of Kolb's learning cycle structured how co-learning activities were put together. At the heart of the activities were the seasonal workshops that were held before the start of each cropping season. The workshops facilitated two elements of Kolb's learning cycle, namely reflective observation and abstract conceptualisation. Farmers' and researchers' experiences from the previous cropping season formed the basis for reflective observation, e.g. on the factors and conditions explaining differences in crop yields. Sharing of experiences during the workshops enriched theories-in-use of participants and facilitated the use of *complementary knowledge*. These exchanges were fostered by creating a safe space and reducing hierarchies, among participants. For example, we, as researchers, opened up about our own learning by discussing uncertainties in workshop content. A considerable part of the workshop content dealt with abstract conceptualisation of the processes playing a role in farm productivity. Each co-learning workshop one or two new concepts were introduced to farmers with the aid of a schematic drawing, a metaphor or a photograph. *Common grounds*

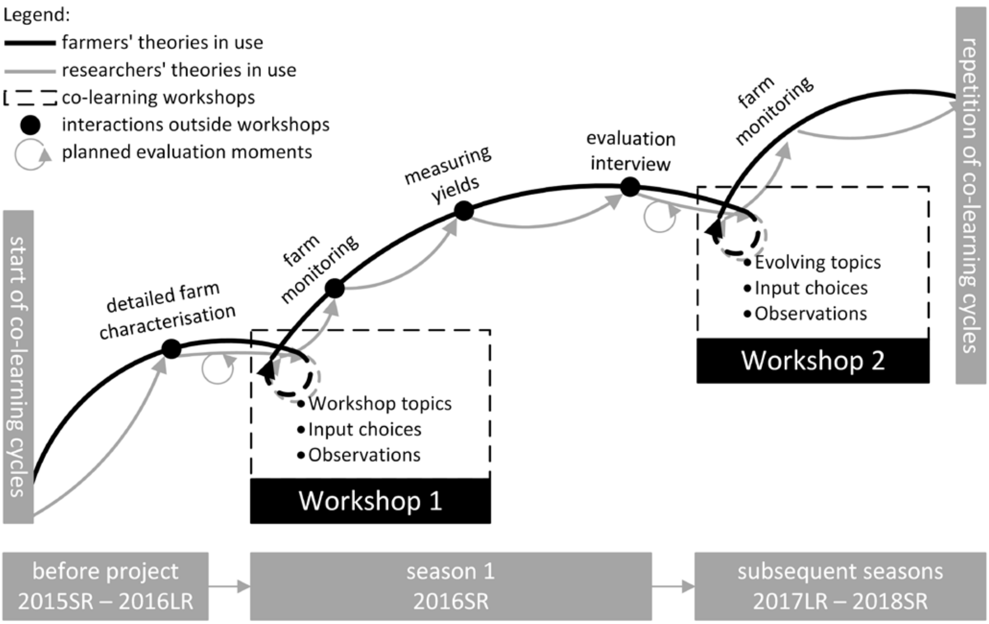

Fig. 2.2: Process diagram of the activities leading to the co-learning workshops each season. All repeated activities and interactions together – monitoring interviews, yield measurements, evaluations interviews and the workshops – formed the co-learning trajectory followed by farmers (black lines) and researchers (grey lines).

developed over time and enabled a shared understanding between farmers and us on the farming system functioning. Developing these common grounds forced us to identify pertinent topics and ways of conveying a message. The ensuing interaction between farmers and researchers about these concepts, informed us on the effectiveness of the communication. Complementary to the workshops, the *input vouchers* supported the other two elements of Kolb's learning cycle, namely, active experimentation and concrete experience. The voucher resulted in a larger decision space, in terms of the amount and diversity of inputs available to farmers. Inputs that were not commonly available in the localities , were made available next to commonly used inputs for maize. The voucher content was linked to the workshop topics and hence evolved over time. The three farm visits each cropping season were used to discuss and monitor farmers' experiences. The evaluation interview ended the seasonal cycle of activities and thereby started the process of reflective observation. Both for farmers and researchers this was a moment to reflect on individual experiences and to take note of emerging questions or issues. Results from the evaluation interviews and the observations made during the other farm visits, were used to determine workshop topics for the following co-learning workshop.

2.3.2 Farmer and researcher learning: evidence from the process of cyclic co-learning

Learning by farmers and researchers took place through various learning loops during the five seasons of co-learning. First, we highlight the specific learning around two major topics: 1) legume cultivation and integration as part of intensified maize-based systems and 2) options to reduce the incidence of striga. Subsequently, we focus on the evolution in workshop topics and communication methods and finally, we reflect on the learning of the researchers.

2.3.2.1 Integrating legumes in intensified maize-based cropping systems

Workshop topics on legumes evolved over the five seasons based on farmers' experiences and changing needs due to intensified maize cultivation. In the first season, soybean was the only legume offered in the vouchers (Table 2.1) and new to most farmers. In the workshops particular attention was given to the possible benefits of soybean, such as rotational effects and presumed market value. However, after the first season co-learning farmers showed widespread discontent with soybean in the evaluation interviews: damage by birds and squirrels and problems of local marketing were major constraints (Supplementary materials 2.1). The second season a groundnut variety new to farmers, *cv.* CG7, and two varieties of common bean, *cv.* KK8 and *cv.* KAT-B-1 were added to the voucher. Common bean is the most commonly cultivated legume in the area. KAT-B-1 was specifically selected for its short duration, as an option to mitigate drought. KK8 was selected for its high yield and its known performance in the area. In the second co-learning season (2017 long rains), rainfall was good and due to increased fertilizer use, maize growth was prolific. Maize yields increased from 1-2 Mg ha^{-1} before the interventions to 4-5 Mg ha^{-1} in the second season. Farmers however, reported that prolific maize growth smothered intercropped legumes (Supplementary

Table 2.1: Inputs included in the voucher during the five seasons of the co-learning trajectory.

Input	Package sizes	Specification where applicable	Commonly available[1]	2016SR	2017LR	2017SR	2018LR	2018SR
DAP[2]	10, 25, 50 kg		Yes	x	x	x	x	x
CAN[2]	10, 25, 50 kg		Yes	x	x	x	x	x
Sympal	2, 10, 25 kg		No	x	x	x	x	x
Maize seed	2 kg	General	Yes	x	x	x	x	x
Maize seed	2 kg	FRC 425IR[3]	Yes		x	x	x	x
Soybean seed	2 kg		No	x	x	x	x	x
Biofix inoculant	10, 20, 50 kg		No	x	x	x	x	x
Dairy meal	10, 25, 50 kg		Yes	x	x	x	x	x
Groundnut seed	2 kg		No		x	x	x	x
Bean seed	2 kg	Medium duration	Yes		x	x	x	x
Bean seed	2 kg	Short duration	No		x	x	x	x
Sorghum seed	2 kg	Only in Busia	No			x	x	x
Silage bags - roll	10 bags		No				x	x
Manure sheet	1 sheet		Yes				x	x
Calliandra	1 seedling		Yes				x	x

[1] Commonly available in agro-input stores in the research sites.

[2] DAP, diammonium phosphate; CAN, Calcium ammonium nitrate.

[3] *cv*. FRC 425IR is an open pollinating maize variety (Fresco seed company) of which the seed are coated with Imazapyr to prevent striga infection

materials 2.1). This was particularly an issue in Vihiga where intercropping is popular due to land scarcity. In response, in the third workshop we introduced sole cropping of legumes and mbili-mbili (double row) intercropping, which improved light availability for the legumes. Although farmers showed great interest during workshops and some made notes about the particular spacing, few tried the alternative spacing option. As the issue of smothering persisted, an extra effort was made during the fourth and fifth seasons by planting demonstration plots together with farmers. After the fifth season, ten out of thirteen co-learning farmers in Vihiga tried one of the alternative legume spacing options on their own farms. In the final evaluation interview, none of the co-learning farmers reported smothering as an issue, indicating that consecutive activities had supported legume integration in intensifying maize cropping systems.

2.3.2.2 Options to reduce striga incidence

Management of striga was not among the workshop topics in the first season, but was included later as a topic that integrated farmers' knowledge and learning with options introduced by researchers. Initially, we had not identified striga as a key issue, but its importance clearly surfaced in evaluation interviews (Supplementary materials 2.1) and farm visits. Options to reduce striga incidence were therefore discussed in the second and third co-learning workshops. These were rotation or intercropping with soybean, use of sufficient manure and mineral fertilizer and a maize variety with Imazapyr (IR) coated seeds (*cv*. FRC 425IR, Fresco seed company) (Fig. 2.3.). The package of IR-coated seeds came with a pair of disposable plastic gloves. One of the wealthier and educated farmers questioned us during the workshop – were these chemical not hazardous? After a brief discussion he noted "*I will not take such seeds, treated with chemicals.*" This statement, by an influential farmer in the community, was likely the reason why none of the co-learning farmers in Busia selected the IR-coated maize that season. In all other groups two to four out of thirteen farmers selected it. Information was repeated in the third season, with less discussion, after which four farmers selected the IR-coated seed option in the co-learning group in Busia. One of them was an elderly widowed woman whose fields were heavily invested with striga. In the evaluation interview after the third season she noted: "*You should not use all the options you presented separately. This season I combined and that works best!*". She had intercropped maize with soybean; applied manure in combination with mineral fertilizer; and planted IR-coated maize. The wealthy farmer who was sceptical early on, visited the female farmer's maize field and noticed the strong performance in the normally heavily infested field. In the following workshop he also selected IR-coated maize. A photograph of the female farmer's field, together with the advice to combine options, was used by the researchers in following workshops. In this example, farmers and researchers learned from each other's knowledge and insights, indicating the importance of complementary and cyclic learning activities.

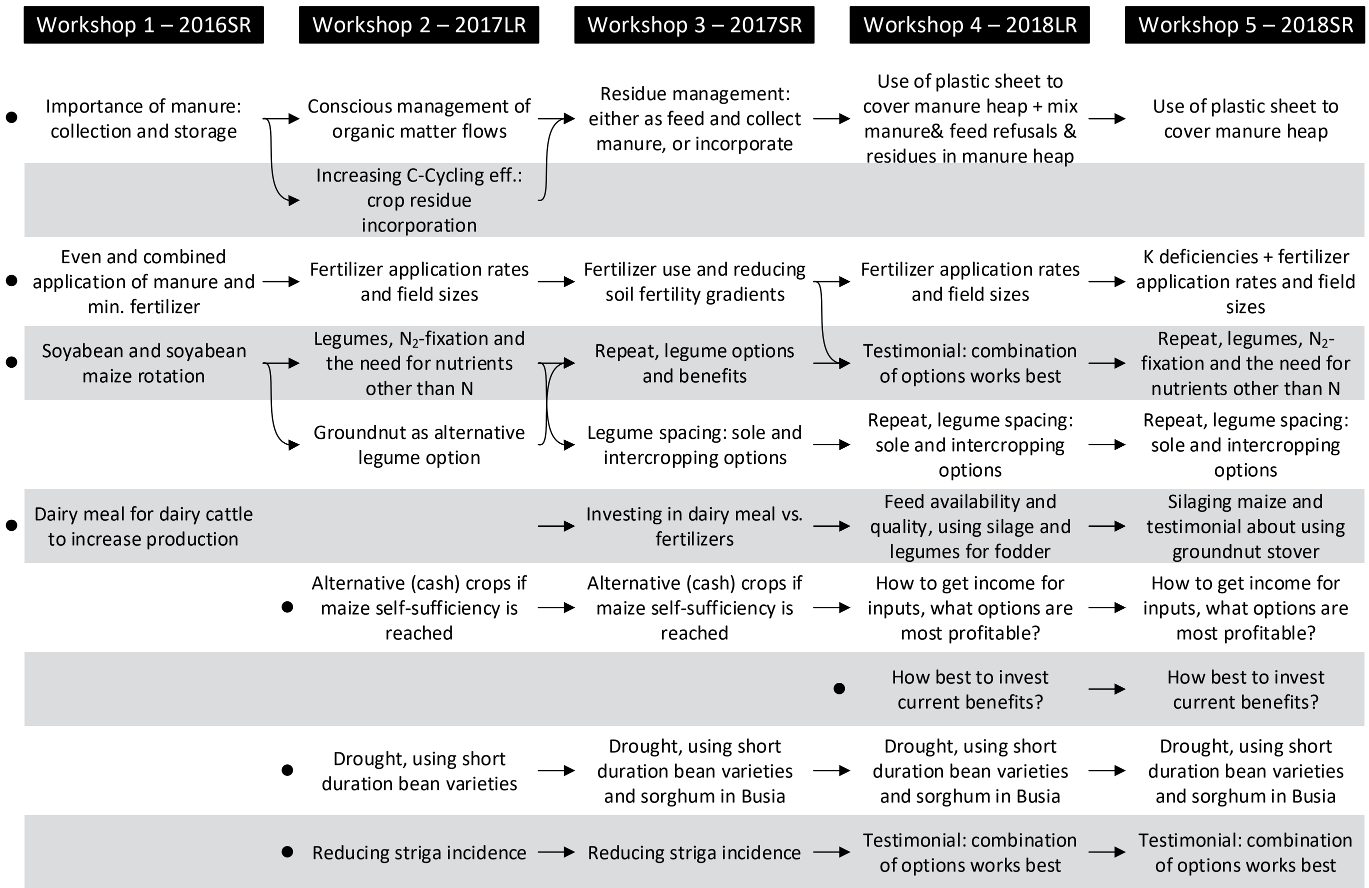

Fig. 2.3: Relational diagram of how workshop topics evolved during the co-learning trajectory. Dots indicate the start of a topic. Arrows indicate a continuing or evolving topic. SR means short rains, LR long rains.

2.3.2.3 Common grounds facilitate shared understanding

Common grounds facilitated the discussions on concepts and processes underlying the functioning of the farming system. Soil fertility gradients turned out to be one of the important concepts as it was introduced in the first co-learning workshop and used in all following workshops (Fig. 2.4A, Table 2.2). Farms in western Kenya commonly consist of fertile home-fields closer to the homestead and infertile out-fields further away due to preferential application of manure and fertilizer to the home-fields (Tittonell et al., 2005b). When soil fertility gradients were discussed the first time, schematic drawings of typical farms were used. The drawing of a farm with no or little livestock and poor maize yields coaxed a chuckle from one of the farmers. She said: "*That is my farm!*", meaning that she linked the conceptual drawing to the mental model she had of her farm. Quotes from following evaluation interviews indicated that farmers had remembered information related to soil fertility gradients, e.g. "*there was a picture of my farm with the different fields*", or "*it is good to distribute manure and mineral fertilizer evenly across the farm*". In the second and later workshops, some farmers noted that, to their surprise, "maize was doing equally well" in poor fields after applying manure and mineral fertilizers. Nine out of thirteen co-learning farmers in Vihiga and nine out of twelve in Busia named something that was related to soil fertility gradients during the final evaluation interview (Table 2.3), indicating that they had understood the concept and applied it on their own farm. Such application of the knowledge, contrary to their previous custom, may indicate that the knowledge was considered relevant. The experience of obtaining similar yield responses to those discussed in the workshop helped in building trust between farmers and researchers.

Table 2.2: New concepts introduced in each workshop with the aim of developing common grounds between farmers and us.

Workshop 1 – 2016SR	Workshop 2: 2017LR	Workshop 3: 2017SR	Workshop 4: 2018LR	Workshop 5: 2018SR
- Soil fertility gradients	- 'Plate of SOC, filled with N, P and K'	- Diagram of C & nutrient cycling: the 'farm cycle'	- Cost-benefit analysis of crops	- Options without inputs of voucher: legume seed recycling and P&K based fertilizers
	- Maize self-sufficiency	- Trade-offs in whole farm production: revenue & maize self-sufficiency	- Legume spacing in intensified systems, field practical	

Table 2.3: Workshop topics remembered by co-learning group farmers in the final evaluation interview. Topics are ordered according to frequency. Topics in italic were not a workshop topic but linked to provision of a voucher. 'Sic' indicates when a topic was never part of the workshops nor related to the voucher.

Workshop topics	Vihiga	Busia
Combining manure and mineral fertilizer	12	9
Soil fertility gradients and even fertilizer application	9	9
Combining options against striga	11	7
Sympal fertilizer for legumes	11	6
Mbili-mbili intercropping and pure stand legumes	9	5
Plastic sheet to cover manure heap	4	8
Maize-legume rotation and intercropping	8	4
Groundnut profitability	4	7
Dairy meal for milk production	7	2
Farm nutrient cycle	3	5
N_2-fixation by legumes	5	3
Fertilizer rates	4	3
Planting in lines	4	3
Timely planting	2	5
Plate of nutrients	3	3
Biofix inoculants for soybean	4	2
To increase production	1	2
Silaging and use of silage bags	2	0
Caliandra as animal feed	2	0
Groundnut residues as animal feed	0	2
Direct application of manure	0	2
Alternatives for when the voucher ends	0	2
Erosion control (sic)	0	2
Using residues as organic input	0	1
Marketability of crops	1	0
'Photos' of our farm	1	0
To use improved seed	0	1
Total workshop topics remembered	*107*	*93*
Number of farmers per group	*13*	*12*

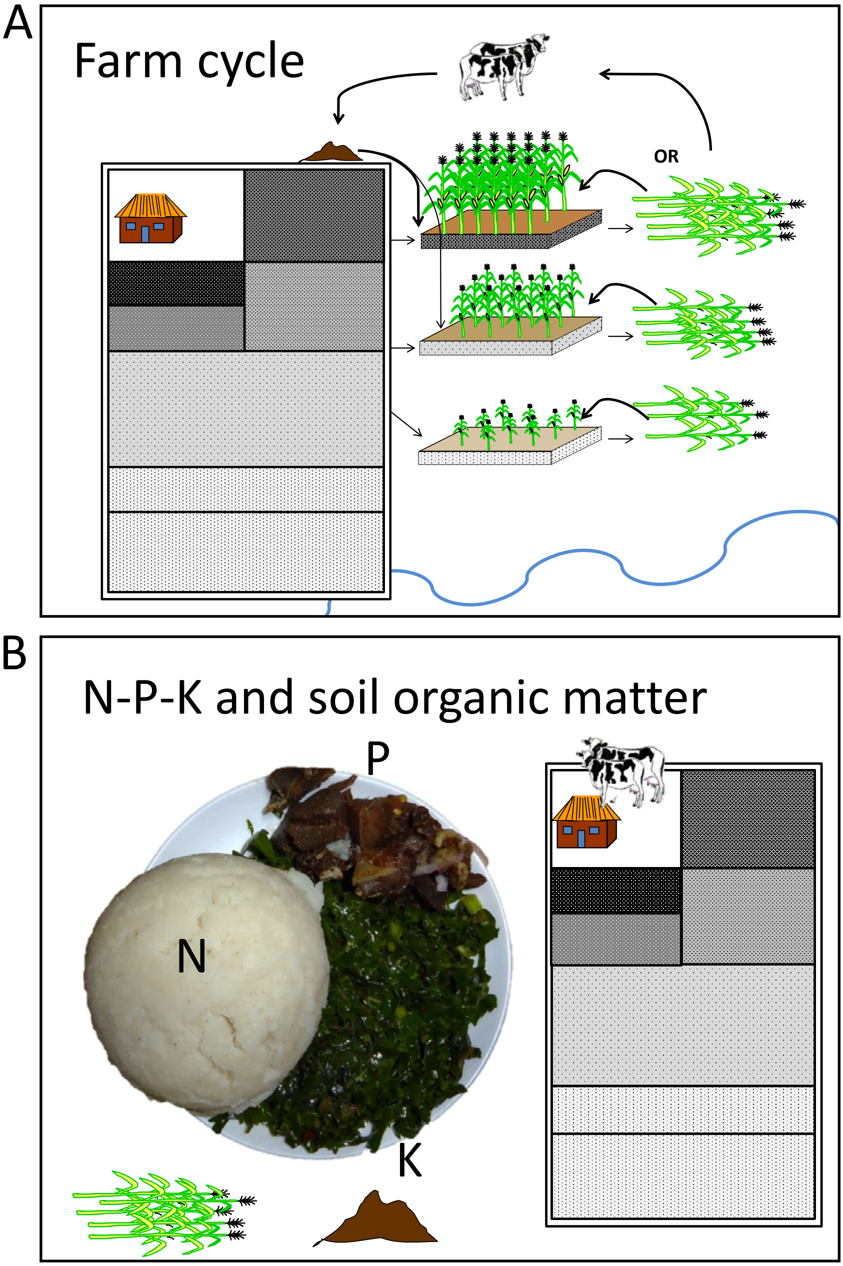

Fig. 2.4: Examples of communication tools used to discuss options for sustainable intensification. A schematic drawing of a farm with a soil fertility gradient (A) presented in the first workshop was used in following workshops to, for instance, discuss the farm (nutrient) cycle. A plate of food was used to discuss the need for balanced nutrition of crops (B). The different types of food represented the different nutrients – N, P and K – whereas the plate itself symbolised soil organic carbon, which was related to the soil fertility gradients.

Another example of a metaphor linking to farmers reality and used to develop common ground, was a plate with three locally common foods – ugali (maize porridge), sukumawiki (kale), and meat (Tittonell et al. 2008a). These foods were used to discuss the need for balanced crop nutrition, needing nitrogen (N), phosphorus (P) and potassium (K) respectively, with the plate itself representing soil organic matter (Fig. 2.4B). The 'plate of foods' was then used to discuss the use of P-based fertilizer (i.e. Sympal) for legumes in following workshops. The soil organic matter was linked to soil fertility gradients and organic inputs such as manure and crop residues, illustrating how different concepts linked to each other as part of the farm system.

Not all communication approaches were an immediate success and we had to learn on the right entry-point to discuss certain concepts. For instance, we expected that maize food self-sufficiency at household level could serve as an entry-point to discuss the minimum area required for growing maize and building on that, the choice for more profitable crops when reaching maize self-sufficiency. Yet, this raised little discussion during the workshops. Subsequent interviews revealed that reaching food self-sufficiency was the most important driver to grow maize. In Busia however, farmers produced over three times more maize than required for self-sufficiency from season two onwards (data not shown). Comments like "*when we have more than we need, we can always sell maize*" were common and illustrated the reliability of the maize market. It seemed that reaching maize self-sufficiency was so important to farmers, that low profit from surplus production was not seen as an issue. As an alternative entry point, the concept of profitability (KSH ha^{-1}) was discussed using the question "*How to earn KSH 10000 (US$100, the size of the voucher) in order to buy inputs for farming*". This proved to be more effective as it resulted in lively discussions around profitability of crops and the relations between profit (in KSH), yield (kg ha^{-1}) and price (KSH kg^{-1}). These results illustrate how our interactions with farmers over multiple seasons changed our theory-in-use of what was a useful entry point in discussions with participating farmers.

2.3.2.4 Researchers learning

Workshop topics and voucher content during five seasons were the result of continuous interactions between farmers and researchers and built on previous topics, experiences, questions and observations (Fig. 2.3). In the second season for instance the following topics originated from farmers' questions and issues: groundnut as alternative legume option, use of short duration (legume) varieties and options to reduce striga incidence. New topics which were solely based on researchers' observations were: fertilizer application rates, and cash generating options in case of maize food self-sufficiency. This was a response to excessive fertilizer application rates observed during monitoring visits, and to increased maize yields which allowed some households to achieve maize self-sufficiency.

In ensuring a safe space, we observed a brittle balance between aiming for open and equal-level discussions and complying with local customs and rules. Our initial intention to reduce the hierarchy during co-learning workshops was difficult to achieve. As an example, when we arrived at the workshop venue, chairs were setup in a classroom-like arrangement by farmers. Although it proved hard to break away from this, over time we managed. The wealthier male farmer reconsidering his opinion about IR-coated maize, based on the experience of the poorer female farmer (section 3.2.2), is an example of how reduced hierarchy enabled co-learning. Besides being explicit about our own learning, we also emphasized the importance of farmers' experiences and knowledge by engaging them in the calculations and assumptions. For instance, before profitability of crops was discussed, the question was raised, "*what can be the yield of maize in one acre?*". Comparing the answers of farmers with our value, opened up a discussion on whether or not our assumption made sense or should be changed. These open discussions thereby contributed to reducing hierarchy, building trust and a shared understanding in which both farmers and us learned from each other's knowledge and experiences.

2.3.3 Farmer learning: evidence from differences between comparison farmers and co-learning farmers

2.3.3.1 Knowledge on farming

Final evaluation interviews revealed two distinct differences in learning outcomes between comparison farmers and co-learning farmers (Fig. 2.5). Firstly, when asked "*What was the most useful you learned during the programme?*", co-learning farmers included knowledge gained from the workshops in their answers. This resulted in more diverse answers from the co-learning farmers, which were specifically linked to the farm system . For instance, the combination of manure with mineral fertilizers and hybrid seed was mentioned most by co-learning farmers. Answers linked to soil fertility gradients also addressed farm-level management. Answers by comparison farmers focused on field level only and were related to inputs provided through the voucher and maize, e.g. timely availability of inputs, sufficient inputs and the use of quality inputs.

Secondly, options mentioned by co-learning farmers were often linked to their individual needs, suggesting that they were contextualising the information from the workshops to their own situation. A co-learning farmer without livestock for instance mentioned that combining mineral fertilizer, hybrid seed and returning crop residues to the fields was most useful to her as she was unable to use manure. Comparison farmers only linked their learning to the voucher content itself and the provision of that voucher.

With respect to the specific question on options to reduce striga, co-learning farmers mentioned more and more diverse options compared with comparison farmers (Table 2.4).

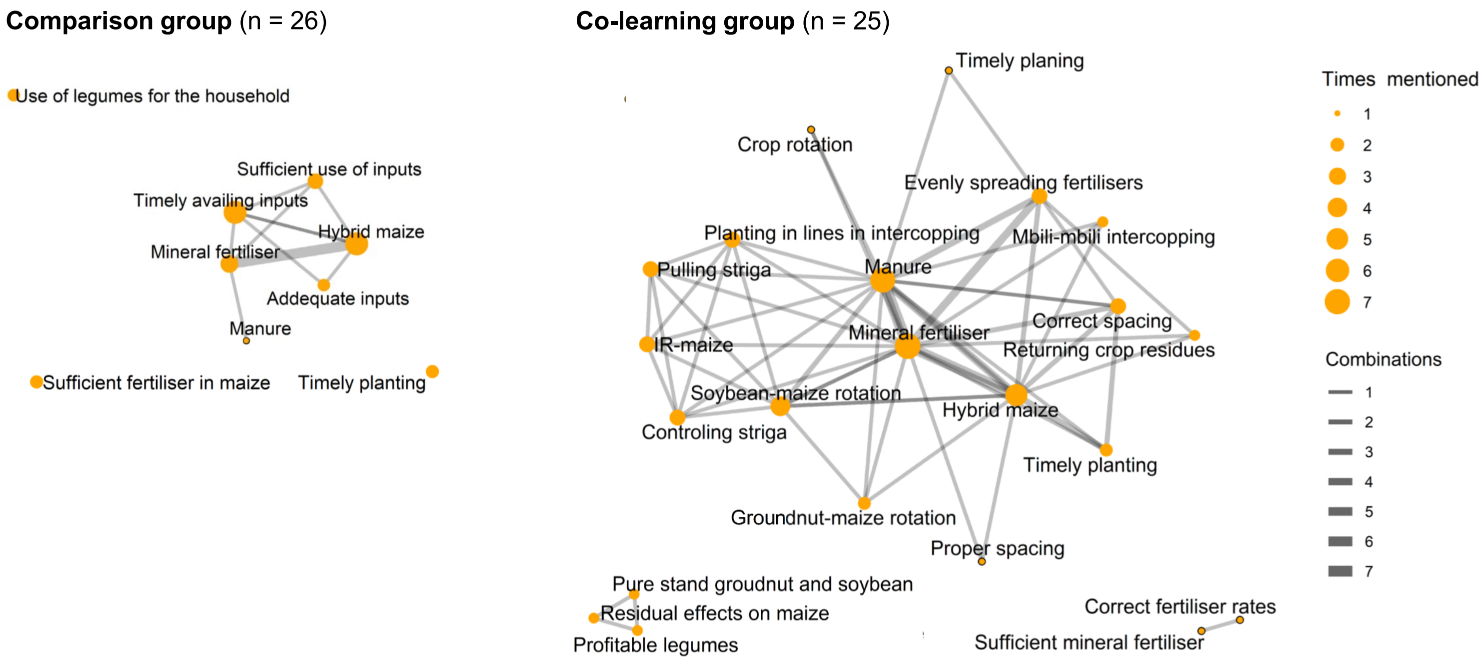

Fig. 2.5: Word-webs of answers given to the question “*What was the most useful of what you learned during the programme?*”. ‘Times mentioned’ (yellow nodes): number of times a learning outcome was mentioned. ‘Combinations’ (connections between nodes): the number of times the two connected learning outcome were mentioned together. For full answers and their frequencies see Supplementary materials 2.2.

Table 2.4: Options mentioned by comparison and co-learning farmers to the question: "*What options do you know to control striga?*"

Options	Vihiga		Busia	
	Comparison	Co-learning	Comparison	Co-learning
Pulling	10	13	8	8
Manure	4	12	11	9
IR coated maize[1]		10		4
Soybean		6		4
Regular weeding	2	1	3	3
Mineral fertilizer		3	1	3
Rotation with soybean		3		2
Desmodium[2]			2	3
Rotation with legumes: soybean, groundnut, common bean			1	2
Rotation with cassava	1		1	1
Other answers (named less than 2 times)			7	4
Total	*17*	*48*	*34*	*43*

[1] IR coated maize are maize seed coated with Imazapyr to prevent striga infection.

[2] Promoted for striga control in previous projects

2.3.3.2 Input choices

No differences in input choices from the voucher between comparison and co-learning farmers were observed (Fig. 2.6). For both groups, maize inputs were most important with an expenditure of on average 60-80 % of the voucher. The higher expenditure on dairy meal by the co-learning farmers in Busia was probably not a result of the workshops as similar choices were made in the preliminary voucher before the first workshop (results not shown). This specific interest for dairy meal may be a result of earlier projects on dairy farming (e.g. by Heifer International, ICIPE, ICRAF) in this region.

2.3.3.3 Changes in farming practices: dynamics in soybean and groundnut cultivation

Co-learning farmers cultivated double the fraction of their farm area with soybean (Vihiga and Busia) and groundnut (Vihiga) compared with the comparison farmers and were continuing the increase in groundnut area (Busia) after five seasons (Fig. 2.7). Comparison farmers had also increased their legume fraction of farm area compared with before the interventions, but after five seasons this was stable or again decreasing.

The fraction of the farm area strongly differed between the two crops, over the five seasons and among farmers. In the first season, only soybean was part of the voucher (Table 2.1).

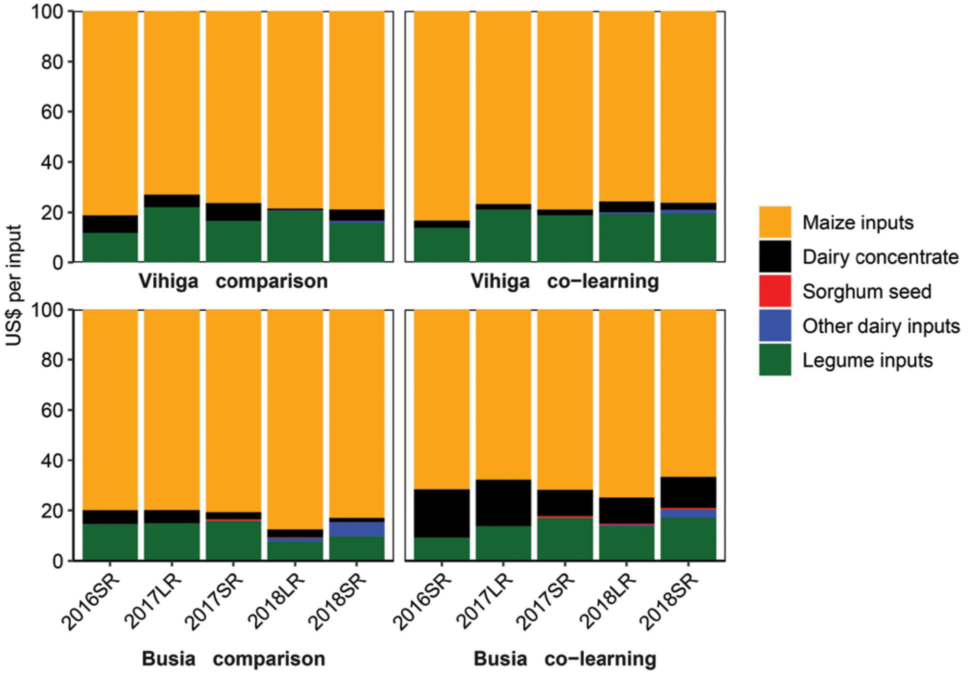

Fig. 2.6: Average expenditure on input types in the input voucher by no-workshops and workshops group farmers in Vihiga and Busia.

Nearly all farmers across groups planted it, on average on ten percent of the farm area. Only 30 out of 51 participating farmers had ever planted soybean before and 4 out of 51 planted it in the two seasons before the project. The soybean area fell sharply in the second season due to pest pressure and problems of marketing. Yet several farmers continued its cultivation on a smaller fraction of the farm. After the fifth season, both the fraction of farm area with soybean and the number of farmers cultivating it, were larger for the co-learning groups in both locations. The reason for cultivation mentioned across groups was home consumption. Reduction of striga and soil fertility improvement were only mentioned by co-learning farmers. In Vihiga, where smothering of soybean and other legumes by maize had become an issue (see Sub-section 2.3.2.1), eight out of thirteen comparison farmers noted this as a reason for reducing soybean cultivation. None of the co-learning farmers mentioned this as a reason.

2.3.3.3 Changes in farming practices: dynamics in soybean and groundnut cultivation

Co-learning farmers cultivated double the fraction of their farm area with soybean (Vihiga and Busia) and groundnut (Vihiga) compared with the comparison farmers and were continuing the increase in groundnut area (Busia) after five seasons (Fig. 2.7). Comparison farmers had also increased their legume fraction of farm area compared with before the interventions, but after five seasons this was stable or again decreasing.

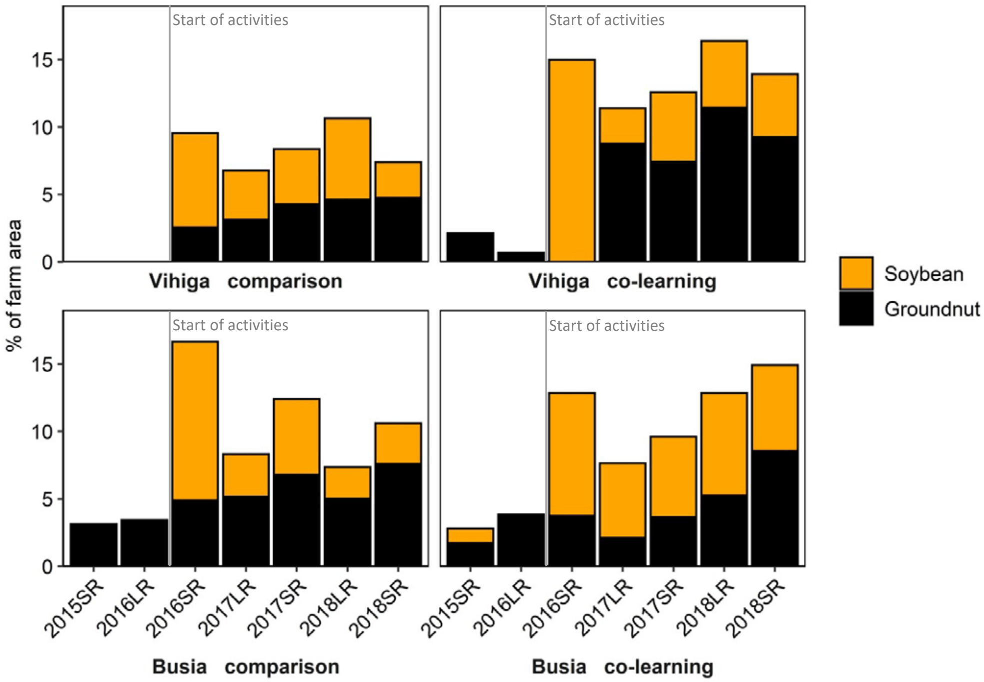

Fig. 2.7: Average fraction of farm area of no-workshops and workshops group farmers with grain legumes in Vihiga and Busia. The dashed line indicates the start of the project.

The fraction of the farm area strongly differed between the two crops, over the five seasons and among farmers. In the first season, only soybean was part of the voucher (Table 2.1). Nearly all farmers across groups planted it, on average on ten percent of the farm area. Only 30 out of 51 participating farmers had ever planted soybean before and 4 out of 51 planted it in the two seasons before the project. The soybean area fell sharply in the second season due to pest pressure and problems of marketing. Yet several farmers continued its cultivation on a smaller fraction of the farm. After the fifth season, both the fraction of farm area with soybean and the number of farmers cultivating it, were larger for the co-learning groups in both locations. The reason for cultivation mentioned across groups was home consumption. Reduction of striga and soil fertility improvement were only mentioned by co-learning farmers. In Vihiga, where smothering of soybean and other legumes by maize had become an issue (see Sub-section 2.3.2.1), eight out of thirteen comparison farmers noted this as a reason for reducing soybean cultivation. None of the co-learning farmers mentioned this as a reason.

In the fifth season a larger fraction of farm area was cultivated with groundnut than with soybean. Main reasons for this were high yields of *cv.* CG7, its large seed and its resistance to groundnut rosette virus, which was a severe problem in western Kenya. Other benefits mentioned by farmers of both groups were the use as food and animal feed (crop residues), improved soil fertility and good marketability. Co-learning farmers however, also noted its ability to fix nitrogen, high price and rotation benefits, which are topics discussed during the workshops topics.

2.4 Discussion

In this study we developed an integrated co-learning approach of which the complementarity of the following elements was novel and turned out to be key: input vouchers, an iterative learning process, common grounds for communication and complementary knowledge. After five seasons, the co-learning farmers had a more diverse and cohesive knowledge on the functioning of their farm than the comparison farmers. One of the tangible outcomes was the continued increase in groundnut and soybean area among co-learning farmers, which resulted in diversification and a likely increase in profitability. We therefore confirm our hypothesis that: *When resource constraints are partly alleviated, co-learning can be effective in changing both knowledge and practices of farmers and researchers*.

2.4.1 Four complementary elements of the integrated co-learning approach

2.4.1.1 A voucher for diverse and increased input use

The voucher provided the opportunity for trying new options, because of its size (USD 100 per season) and the diverse agricultural inputs offered. The possibility to increase inputs rates led to new farmer experiences, for both poorer and better-off. Reflective observation on failures (or successes) stimulated farmers to try again, avoiding previous mistakes. Direct-cash handouts, as an alternative to the more traditional development aid (e.g. Bastagli et al. 2016; Blattman et al. 2018) serve the same purpose, but can be spent freely, with the underlying assumption that beneficiaries know best how to spend their money. Sometimes a training element is attached (Blattman et al., 2016). Our voucher was limited to agricultural inputs selected by researchers, thereby limiting the decision space of farmers. The voucher however effectively increased input use and yields, directly supporting household and local level food self-sufficiency. Somewhat surprisingly, no differences were found between comparison and co-learning farmers in input choices with the voucher. This could be attributed to the overriding importance of maize for farmers in western Kenya and dairy cows for farmers who own them. In addition, certain inputs such as legume seed, can be re-used from own saved seed, so that farmers may have changed their management without changing input choices.

2.4.1.2 Iterative learning cycles

There are few studies (e.g. Dogliotti et al., 2014; Falconnier et al., 2017) in which co-learning with smallholder farmers took place over multiple seasons and focused on whole farm productivity. Thanks to the bi-modal rainfall pattern, five iterations in three years resulted in short feedback loops, spurring rapid learning. The cyclic learning activities facilitated all four stages in Kolb's learning cycle and thereby supported the different styles of learning. Similar to Willemsen et al. (2007) the iterative cycles were also important for reducing the hierarchy within the group and thereby changing the individual's attitude and participation. This supported the convergence of theories-in-use (van Mierlo et al., 2010) on workshop topics and initially conflicting views (Wals and Heymann, 2004).

The effectiveness of iterative cycles points at the need for a prolonged time in learning processes (Srinivasan and Elley, 2018). Throughout the five seasons, new questions and issues continuously arose. The number of iterations needed to conclude a topic depended on its complexity, whereby we sometimes had to find out first how to communicate and whether additional hands-on activities were needed. Given the dynamic nature of farming however, questions and issues will never cease to arise, indicating a need for continuous co-learning. Farmer field schools (Braun et al., 2006) aim to establish continuity in life-long learning, but differ from our approach, which actively integrates external knowledge with farmers' knowledge, questions and issues.

2.4.1.3 Communication based on building common grounds

Building a common understanding among farmers and researchers was an integral part of the approach. The use of tools like pictures and drawings is often advised when communicating with smallholders (e.g. Leeuwis and Van den Ban 2004). Defoer et al. (1998) used participatory resource flow mapping to discuss resource flows on the farm; Ramisch et al. (2006) used localised names for nutrients N and P; and Tittonell et al. (2008) used the 'plate with nutrients' to discuss soil sample results. We incorporated some of these ideas into this part of the integrated co-learning approach.

Soil fertility gradients constituted an important concept for communication because it was central to the system and easily recognised by farmers – "*That is my farm!*". Farmers easily recognised a typical farm level concept like soil fertility gradients, because of its link to their unit of decision making: the farm or household level (Giller et al., 2006). This shared basis then allowed discussions on the link between soil fertility and input use efficiency in particular in relation to the increased fertilizer use enabled by the voucher. Moreover, the link between soil fertility gradients and several farm components made it easy to include manure management and the farm nutrient cycle in the discussion. Similar recognisable patterns of variability in soil fertility at farm level can be found across SSA (Giller et al., 2011, 2006), making it a useful starting point for the development of common grounds in a variety of contexts.

2.4.1.4 Complementary knowledge: farmers and researchers

The knowledge from both farmers and researchers drove the evolving co-learning process. On the one hand, farmers' knowledge and experiences helped understanding what options worked where (e.g. soybean experiences) and resulted in new insights for us on the combination of options against striga. In a more agronomy-focused study, Falconnier et al. (2016) also found that farmers' experiences were helpful in explaining variability in yield responses. On the other hand, the external knowledge of researchers introduced new options and perspectives on experiences (e.g. prolific maize growth) that were previously not known or recognised by farmers. Hence, relying only on the final steps of the ladder of participation (Pretty, 1995), where farmers fully take the lead, may not be the most effective, as farmers' knowledge may be limited by their current experience. Ramisch et al. (2006), for instance, describe how farmer-led ISFM experiments lack new options when researchers are less involved. We found that incorporating farmers' observations in the workshops allowed to contextualize generic options to the local conditions (Descheemaeker et al., 2019).

Earlier research in western Kenya on nutrient use efficiency along fertility gradients (e.g. Vanlauwe et al. 2006; Njoroge et al. 2019), crop rotation benefits of legumes (e.g. Kihara et al. 2010), longer-term soil fertility impacts (e.g. Sommer et al. 2018; Sprunger et al. 2019) and farming system functioning (e.g. Crowley and Carter 2000; Tittonell et al. 2005a, b) was relatively plentiful and provided important information about potential options for improved farm performance. In areas with limited prior research, additional on-farm research may be needed to inform farmers and researchers on the selection of options. Although not part of the design of the integrated co-learning approach, the knowledge of experienced local field officers and their interactions with farmers enabled agile responses to emerging issues. Local field-officers contributed valuable information that was not available in scientific or grey literature, such as on suitable legume and maize varieties.

Only few studies evaluated the learning by researchers in participatory research (e.g. Falconnier et al. 2017). This is regrettable because a critical evaluation of possible dissonances between researchers' and farmers' knowledge and understanding (e.g. on IR-coated maize) may be essential in developing shared knowledge (Hazard et al., 2018; Ramisch, 2014). The work of McCown and colleagues (Carberry et al., 2002; McCown et al., 2009) on decision support tools in agriculture reflects on how they as researchers learned from interacting with farmers, and how this allowed them to rethink their approach. Similar to our findings, they point at the need for developing trust between farmers and researchers to share knowledge, new insights and possible dissonances.

2.4.2 Integrated co-learning in legume cultivation

The dynamics in farm area cultivated with legumes indicated that there was both an effect of the integrated co-learning activities and of the voucher in the absence of the co-learning activities. We attribute the chance in practice of co-learning farmers to the integrated co-learning trajectory, which removed both financial and knowledge constraints. Tittonell and Giller (2013) noted that, under current conditions, cash may be more constraining for smallholder farmers to increase yields, than knowledge or technologies. However, by improving the access to inputs we may have reached the point where knowledge became limiting. Nevertheless, just providing legume inputs through a voucher also stimulated comparison farmers to increase their legume area. Current restricted availability of legume seed and other inputs is a 'cause and effect' dilemma: farmers prioritise maize inputs resulting in less demand while agro-input dealers and seed multipliers do not stock legume inputs because of the low demand, reducing the availability of legume inputs for farmers.

We evaluated the effectiveness of the integrated co-learning activities based on the dynamics in the cultivated area of legumes. In the case of soybean, only farmers who saw specific benefits, e.g. striga reduction or crop rotation benefits, continued or started cultivating it. Many others stopped or reduced the area with soybean after the initial 'try-outs'. These try-outs and slowly-developing uptake trends point to the complexity of evaluating adoption of a new crop or technology, which underpins the argument that adoption studies should go beyond an evaluation at a single point in time (Glover et al., 2019).

2.4.3 Reflection on research setup

To test the integrated co-learning approach, we compared differences in learning, farmer choices and practices of farmers in comparison groups, who received a voucher only, and co-learning groups, who also participated in co-learning activities. We did not include a full control group, without a voucher and no co-learning, nor did we include a group engaged in co-learning without a voucher, because farm monitoring and yield sampling visits were too time demanding. Moreover, we expected drop-outs (Aklilu, 2007) as well as other difficulties in collecting data for full control groups without a voucher. As alternative for the full control, we considered the situation on the farms before the start of the project (Fig. 2.7). This may not rule out that some observed changes could have happened in absence of our project. Furthermore, it was difficult to differentiate the learning by the comparison and co-learning farmers through the options offered with the voucher. The voucher options evolved for both groups, but these changes were based on interactions with the co-learning farmers. As this reduces the potential differences between the two groups, we do not consider this as a major limitation of our study. In this study we also did not test what happened after the integrated co-learning approach ended, precluding an assessment of the prolonged effects of the programme. Nevertheless, in particular the poorer households may find it difficult to benefit from what they learned as continuing the levels of input use may not be attainable for them. Moreover, the economic risks associated with more intense input use and low availability of diverse inputs may be a problem for all farmers without the external support.

2.4.4 Integrated co-learning approach or its separate parts for sustainable intensification?

Five seasons of integrated co-learning led to sustainable intensification of the farming system. From a sustainability perspective, the approach addressed the three pillars of 1) environmental, 2) economic, and 3) social sustainability. The incorporation of legumes in the cropping system may result in rotational benefits and the even distribution of manure and mineral fertilisers across the farm may reduce losses, thus contributing to environmental sustainability. Legumes such as groundnut were more profitable and nutritious than maize, so that their inclusion improved both economic and social sustainability. Increased yields and food self-sufficiency as a result of increased input use through the voucher also contributed to economic sustainability. Moreover, the more in-depth understanding of co-learning farmers on their farm system may empower them in improving future farm management and responding to hazards (e.g. striga infestation), which benefits social sustainability. From an intensification perspective, increased input used resulted in increased yields. A more detailed analysis is however required to assess whether field and farm level input use resulted in more sustainable farm management for co-learning farmers than comparison farmers and whether this resulted in yield differences, which is the scope for future research. Although we developed the approach for initiating sustainable intensification, it may have a wider applicability in processes where learning and investments are intertwined and not easily started off by farmers, e.g. for biodiversity inclusion or adaptation to climate change.

Applying the integrated co-learning approach on a larger scale would require considerable investment, both in terms of subsidised inputs and people, in particular when compared with the deplorable state of extension and government investments in agriculture in Kenya (Poulton and Kanyinga, 2014). This raises the question whether the elements of the co-learning approach can also be used separately and how this could be operationalized in the context of the East African highlands. Just supplying vouchers would be costly but relatively simple. Our study indicates however that feedback on the options on offer was essential to fit local conditions. Intensive testing and monitoring the use of voucher inputs in some localities would be an option to develop a locally-relevant voucher. Likewise, common grounds could be developed and tested in a few localities and then integrated in a mobile phone or other ICT-based application to extend to surrounding localities. Users of this application could also be given the opportunity to report new issues or questions, resulting in a form of citizen science (c.f. Van Etten et al., 2019), improving the scalability of the approach. Such a combined approach of providing a voucher in combination with knowledge through an application could also be of interest to NGOs such as OAF (www.oneacrefund.org), who provide inputs on loan to smallholder farmers. The use of separate elements on their own is less likely to be as effective as compared with the combination of all four elements in our integrated co-learning approach. Testing the elements on their own requires further research as we tested the use of an integrated approach in a similar fashion as Banerjee et al. (2015), and not the separate parts.

2.5 Conclusions

In this paper we successfully developed and tested an integrated co-learning approach for fostering sustainable intensification in smallholder agriculture. We found that the integration of the following four elements was key in achieving the learning outcomes. 1) A USD 100 input voucher enlarged the decision space and resulted in new experiences and outcomes, stimulating the need for learning on new options for a diverse group of farmers. 2) These new experiences and outcomes were supported by iterative co-learning activities which were repeated several seasons, thus building up knowledge. 3) Concepts underlying the farming systems were communicated by developing common ground between farmers and researchers, resulting in a better understanding of the farming system for both farmers and researchers. 4) Complementary knowledge of farmers and researchers contributed to developing contextualized options for sustainable intensification. The gradual development of trust and convergence of theories-in-use point at the need for multiple seasons of learning, preferably as part of continuous interaction between farmers and for instance extension agents. We found that farmers taking part in the co-learning process developed a richer understanding of the interactions between farm system components, illustrated by a continued increase in groundnut and soybean area, which led to more diversified and intensified maize cropping systems. Besides providing unique evidence of the application of co-learning, this study showed that changing the current availability of capital and knowledge through an integrated co-learning approach can be effective to move towards sustainable intensification.

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Chapter 3

Narrowing yield gaps does not guarantee a living income from smallholder farming – An empirical study from western Kenya

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Marinus, W., Descheemaeker, K., van de Ven, G.W.J., Vanlauwe, B., Giller, K.E., (submitted). Narrowing yield gaps does not guarantee a living income from smallholder farming – An empirical study from western Kenya.

Abstract

Crop yields in sub-Saharan Africa need to increase to keep pace with food demands from the burgeoning population. Smallholder farmers play an important role in national food self-sufficiency, yet many live in poverty. Investing in inputs to increase yields is therefore often not viable for them. To investigate how to unlock this paradox, whole-farm experiments can reveal which incentives could increase farm production while also increasing household income.

In this study we investigated the impact of providing farmers with a USD 100 input voucher each season, for five seasons in a row, on maize yields and overall farm level production in terms of value of produce in two contrasting locations in terms of population density, Vihiga and Busia, in western Kenya. We compared the value of farmers' produce with the poverty line and the living income threshold.

Crop yields were mainly limited by cash constraints and not technological constraints as maize yield immediately increased from 16% to 40-50% of the water-limited yield with the provision of the voucher. In Vihiga, at best, one-third of the participating households reached the poverty line. In Busia half of the households reached the poverty line and one-third obtained a living income. This difference between locations was caused by larger farm areas in Busia. Although one-third of the households increased the area farmed, mostly by renting land, this was not enough for them to obtain a living income. Our results provide empirical evidence of how a current smallholder farming system could improve its productivity and value of produce upon the introduction of an input voucher. We conclude that increasing crop yields of currently most common crops cannot provide a living income for all households and additional institutional changes, such as alternative employment, are required to provide smallholder farmers a way out of poverty.

3.1 Introduction

Crop yields must increase in sub-Saharan Africa (SSA) to keep pace with the food demands of the growing population, to preserve important natural ecosystems and to achieve food self-sufficiency at national and regional level (Jayne and Sanchez, 2021; Thornton et al., 2018; van Ittersum et al., 2016). Yields of major cereals have increased only moderately over the past decades, reaching generally only about 20% of the water-limited yield. If current trends continue, SSA cannot achieve self-sufficiency in food in 2050, which would require narrowing the yield gap to at least 50% of the water-limited yield (van Ittersum et al., 2016). Smallholder farmers currently contribute about 70% to the national food production (Samberg et al., 2016). For the required yield increases however, their farming objectives may not match national production goals (Giller, 2020), as food and income generation to meet family needs prevail. Small farm areas represent an important limitation for farmers to realise significant additional farm revenue through investing in farming (Harris and Orr, 2014; Ritzema et al., 2017). Moreover, limited and risky returns on investment act as a disincentive to purchase inputs such as fertilisers (Jindo et al., 2020; Tittonell et al., 2007).

The farmers' perspective is often overlooked in studies that analysed interventions designed to increase production, e.g. in Ethiopia (Abate et al., 2015; van Dijk et al., 2020). At the same time, empirical farm level studies that try to identify options for improvement often operate within the boundaries imposed by current constraints (e.g. Falconnier et al., 2017; Ronner et al., 2019), which limits the 'solution space' (Martin et al., 2013). On-farm experiments at field level, often in researcher-managed plots, have shown repeatedly that strong increases in crop yields are technically feasible by increasing input use (e.g. Bekere et al., 2021; Njoroge et al., 2017; van Loon et al., 2019). Smallholder farms often show large differences in soil fertility, in crop productivity (Tittonell et al., 2005b; Zingore et al., 2007a), and in yield responses to inputs, such as fertiliser (Franke et al., 2019; Vanlauwe et al., 2006; Zingore et al., 2007b). Part of these differences are explained by the large diversity between households within farming communities in terms of income, farm area and other characteristics (Giller et al., 2011). There is a scarcity of information however on farmers' decisions on input use and the effects on yield over multiple seasons (e.g. Burke et al., 2020). Moreover, few empirical examples show whether it is possible to increase yields in all fields of a farm (e.g. Sanchez et al., 2007) and what would be needed to stimulate increased input use. Input subsidies, e.g. through vouchers, are one option to alleviate household financial constraints for buying inputs and have become common in the past two decades across SSA (Jayne et al., 2018). They mostly focus on inputs for maize or other important staple crops and aim to reduce poverty and raise household income through increasing production (Jayne et al., 2018).

The overall aim of our study was to observe and understand diverse farmers' responses over multiple seasons to provision of input vouchers. Each farmer received a voucher worth USD100 which they could spend on agricultural inputs supplied by the project. We monitored farmer responses and the impacts of the vouchers on farm productivity and income. Rather than simply comparing their income with the poverty line, which covers the bare minimum needed to live, we used another benchmark of a living income. The living income benchmark considers the income needed for a 'decent living' (Anker and Anker, 2017a; van de Ven et al., 2020). Our specific objectives were: 1) To assess the impact on maize yield and overall farm level production of providing a USD100 input voucher during five seasons; 2) To assess whether the changes in production are sufficient to lift a household out of poverty or provide a living income; 3) To assess the extent to which land available for cropping constrains overall production.

3.2 Methodology

3.2.1 Study area

The study took place in two locations in western Kenya. Vihiga county is a typical highland area, with a population among the densest in SSA, ~1050 people km^{-2}, and farm areas covering less than 0.5 ha. Busia county is a medium altitude area with a moderate population density, ~550 people km^{-2}, and farm areas around 1.0 ha (Jaetzold et al., 2005; KNBS, 2019). Both locations have a bi-modal rainfall pattern typical of the East-African Highlands, with two cropping seasons per year. The long rains (LR) last from March until June and the short rains (SR) from September until November. Total rainfall in both locations is 1800-2000 mm year^{-1} (Jaetzold et al., 2009a, 2009b). Maize is the most important staple crop. It is often intercropped with common bean and both crops together cover about 50% of the farm area. A more detailed description of the research area is given in Marinus et al. (2021).

3.2.2 The input voucher

An input voucher was issued in five subsequent seasons, from 2016SR season until 2018SR. A workshop was organised before each season in which farmers could select agricultural inputs from a list to a maximum value of USD100. The value was based on the maximum first loan farmers could obtain from One Acre Fund (OAF), which increased to a maximum of USD 270 per season after repayment of the first loan (OAF, 2016). OAF is a social enterprise providing inputs on credit to farmers in the region (www.oneacrefund.org). Based on farmers' feedback and researchers' observations, different inputs were added to the list over time (Marinus et al., 2021). The inputs included maize, groundnut, soybean, common bean and sorghum seed, mineral fertiliser (diammonium phosphate (DAP), calcium ammonium nitrate (CAN) and Sympal legume fertiliser, soybean inoculant (Biofix, MEA Ltd - Kenya), and other inputs (Marinus et al., 2021). About half of these inputs were commonly available at agro-input dealers in towns frequented by the farmers. The other inputs were sourced from other places in western Kenya. All inputs were delivered to the farmers by the project. Farmers used on average 80-95% of the voucher value on inputs for maize, groundnut, soybean and common bean (Marinus et al., 2021).

In both Vihiga and Busia two sub-locations with 11-12 farmers each were selected. Farmers in one of the two sub-locations took part in a co-learning trajectory (Marinus et al., 2021). All farmers received the same voucher and there were no significant differences in grain yields and income from farming between the sub-locations (Marinus et al., 2021).

3.2.3 Detailed farm characterization and farm monitoring

Detailed data on farm productivity and farm management were collected for seven seasons. During the two seasons prior to issuing the input voucher (2015SR and 2016LR) data were collected using a detailed farm characterization survey (DFC), following the approach described by Giller et al. (2011). During the first survey, general questions were asked, such as household size and composition, and a map of the farm was drawn. During a second visit, all fields were visited and data on field management and production were collected. Field size was measured using a hand-held GPS or using a tape measure in case of fields with sides less than 20 m.

The same researcher visited all fields during each of the five seasons when farmers received the voucher. During a mid-season visit he observed the crops cultivated and asked about input use in each field. Grain yields of the voucher crops – maize, groundnut, soybean and common bean – were assessed by means of crop cuts. Two 4 × 4 m (16 m^2) quadrats were placed in each field. Fresh cob (maize) and pod (legumes) yields were measured in the field, and one sub-sample per quadrant was taken to determine oven dry weight. Dry weights were calculated back to a standardized moisture content of 14% and the grain yield (kg ha^{-1}, referred to as 'yield' hereafter) per field was calculated as the average of the two quadrats. The farm-level yield (kg ha^{-1}) per crop was calculated as a weighted average of the fields containing that crop relative to the total area of that crop per farm.

Farm area was monitored throughout the intervention. If fields were added to a farm, it was noted whether these new fields were bought, borrowed, rented-in or whether this was family land that was now used by the household while earlier being lent or hired out.

3.2.4 Indicators and benchmarks

3.2.4.1 Water-limited yield

Maize yields were compared with the average water-limited yield from the Global Yield Gap Atlas (GYGA) for the Kakamega climate zone, covering both Vihiga and Busia. Those water-limited yields were converted to a moisture content of 14%. For the short rainy season the water-limited yield was 8.0 t ha^{-1} and for the long rainy season, 12.5 t ha^{-1} (GYGA, 2020).

3.2.4.2 Value of produce, poverty line and living income

The farm-level value of produce (named value of produce hereafter) was calculated as the measured crop production per season of all fields containing maize, groundnut, soybean and common bean multiplied by their respective median prices for 2018. The median price was assessed through a weekly market survey in both sites. We used the median crop price of 2018 across both sites as prices hardly differed during the season (Supplementary materials 3.2). The value of produce was expressed per adult equivalent per day based on the household composition in 2018, following OECD (2011) and Van de Ven et al. (2020), and the proportional contribution of the short and the long rains cropping seasons to the annual production. Input costs were not considered as these were largely covered by the voucher. The value of produce calculated therefore paints a relatively optimistic figure and does not necessarily reflect profitability of the farm. The poverty line was based on World Bank, (2015) and the living income on Anker and Anker (2017b). Both were corrected for inflation, using 2018 as reference year, similar as for the crop prices. Both the poverty line and the living income were expressed in Kenya Shilling per adult equivalent.

3.3 Results

3.3.1 Farm-level maize yields

The maize yield averaged across the farms, increased from 1350 kg ha^{-1} (2015SR) and 850 kg ha^{-1} (2016LR) before the voucher was introduced, to 3800 kg ha^{-1} and 5400 kg ha^{-1} for the short and the long rains respectively, after introduction of the voucher (Fig. 3.1A). Hence, maize yields increased from less than 16% to 40-50% of the water-limited yield (Fig. 3.1B). This increase occurred immediately in the first season the voucher was issued, with no further increase in subsequent seasons. Yields before voucher introduction showed a wide variation with very low yields in the 2016LR season due to drought.

3.3.2 Value of produce

Value of produce per adult equivalent more than tripled from the first season with the voucher onwards, compared with the seasons without a voucher (Fig. 3.2). This was mainly a result of the threefold increase in yield. An increase in cultivated area of the four voucher crops from about 40-50% to 60-70% of the farm area (data not shown) resulted in an additional increase from the second season onwards. The value of produce in two-thirds of the households in Vihiga never even reached the poverty line and it was above the living income threshold for only one of the households in some seasons. In Busia the value of produce from the four crops was more than the poverty line for half of the households and above the living income threshold for about one quarter of the households in two out of five seasons. Groundnut, common bean and, to a lesser extent, soybean were important crops in terms of value of produce, in particular in Busia. The value of produce of maize alone was sufficient for

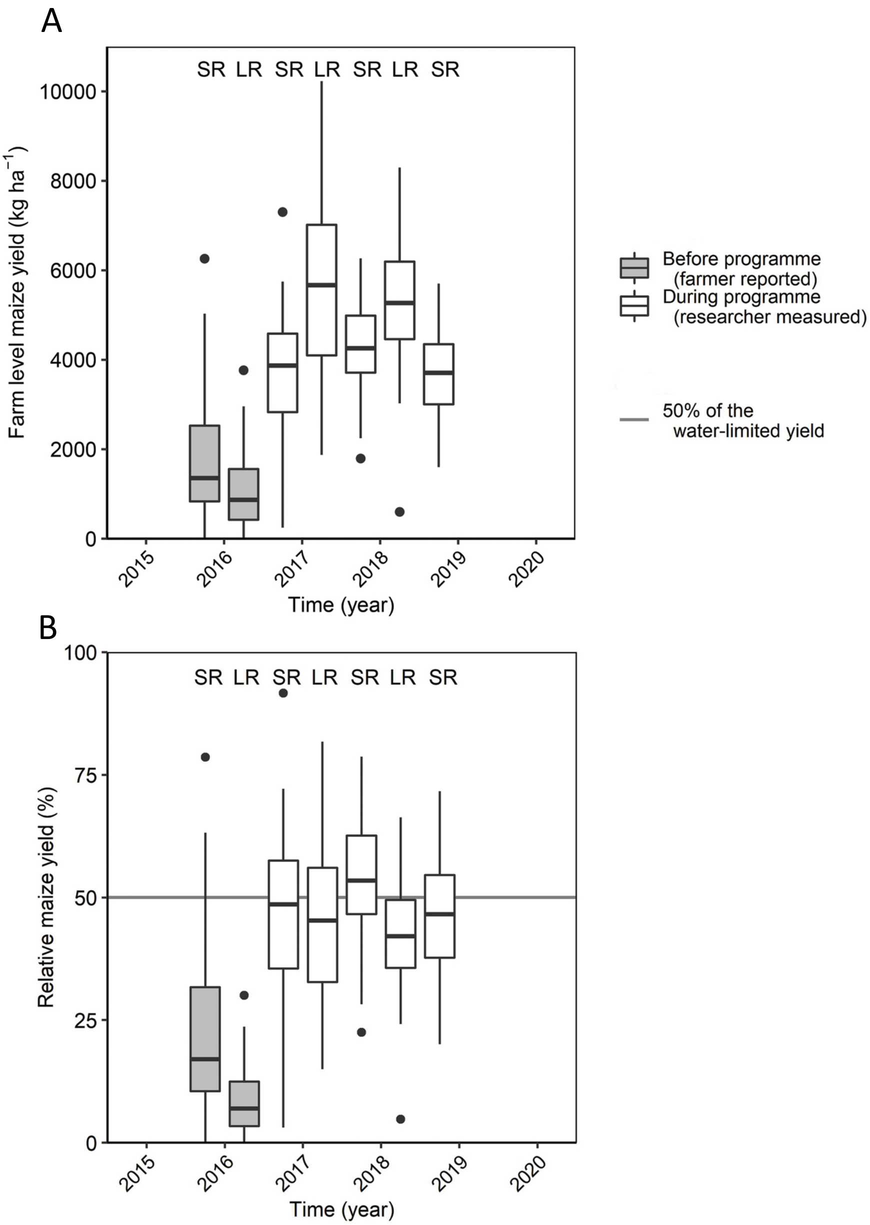

Fig. 3.1: Farm level maize yields in absolute values (A) and relative to the water-limited yield for the short (SR) and long rain (LR) cropping seasons (B) (n = 47 households with 1-8 maize fields per household). Yields before the programme were based on farmer-reported production and measured field sizes, while during the programme with the voucher available both were measured by researchers. The horizontal line indicates 50% of the water-limited yield.

two households in Busia to achieve a living income.

For a number of households, value of produce remained low, in particular in Vihiga (households 3, 4, 6, 18 and 20, Fig. 3.2), but also for some in Busia (households 7 and 16). These were mainly women-headed households with few household members and/or households with an ultra-small farm area of less than 0.2 ha (Fig. 3.3). For them, the limited labour availability and the small farm area precluded a useful allocation of the inputs from the voucher, and as a result, part was given away or not used, as was reported in the monitoring survey. Household level production therefore only increased to a limited extent and sometimes was even less than the voucher value (Supplementary materials 3.3).

3.3.3 Changes in farm area during the voucher intervention

Farm area increased for 8 out of 23 households in Vihiga and 14 out of 24 households in Busia after the voucher introduction (Fig. 3.3). Most of this land was rented or family land that had been fallow before, the latter mainly in Busia. Only three households bought additional land. The initially small farms more often expanded their area than the larger farms, in particular in Vihiga (Fig. 3.3, Supplementary materials 3.4). Absolute increases in farm area were largest in Busia (Fig. 3.3). Farmers reported that they wanted to make good use of the inputs and needed more land. For instance, Household 1 in Vihiga was a single-headed male household who initially owned only a small plot around his house. The farmer worked off-farm in a nearby town before the intervention and sold self-made charcoal. The voucher enabled him to borrow land from a relative who was living away in the city and to rent in land in later seasons. Thanks to this increase in farm area he moved from being among the households with the lowest value of produce to the group of farmers with a high value of produce (Fig. 3.2.). In Busia, farmers increased their farm area mainly to boost production and sell the surplus. However, rent agreements were often informal and only held for single seasons, leaving farmers to search for new rental land. Land owners often refused to rent out their land for a subsequent season as they also wanted to profit from the high yields obtained with the voucher inputs. Only one household reduced the farm area as a field was given away to their son for building his house.

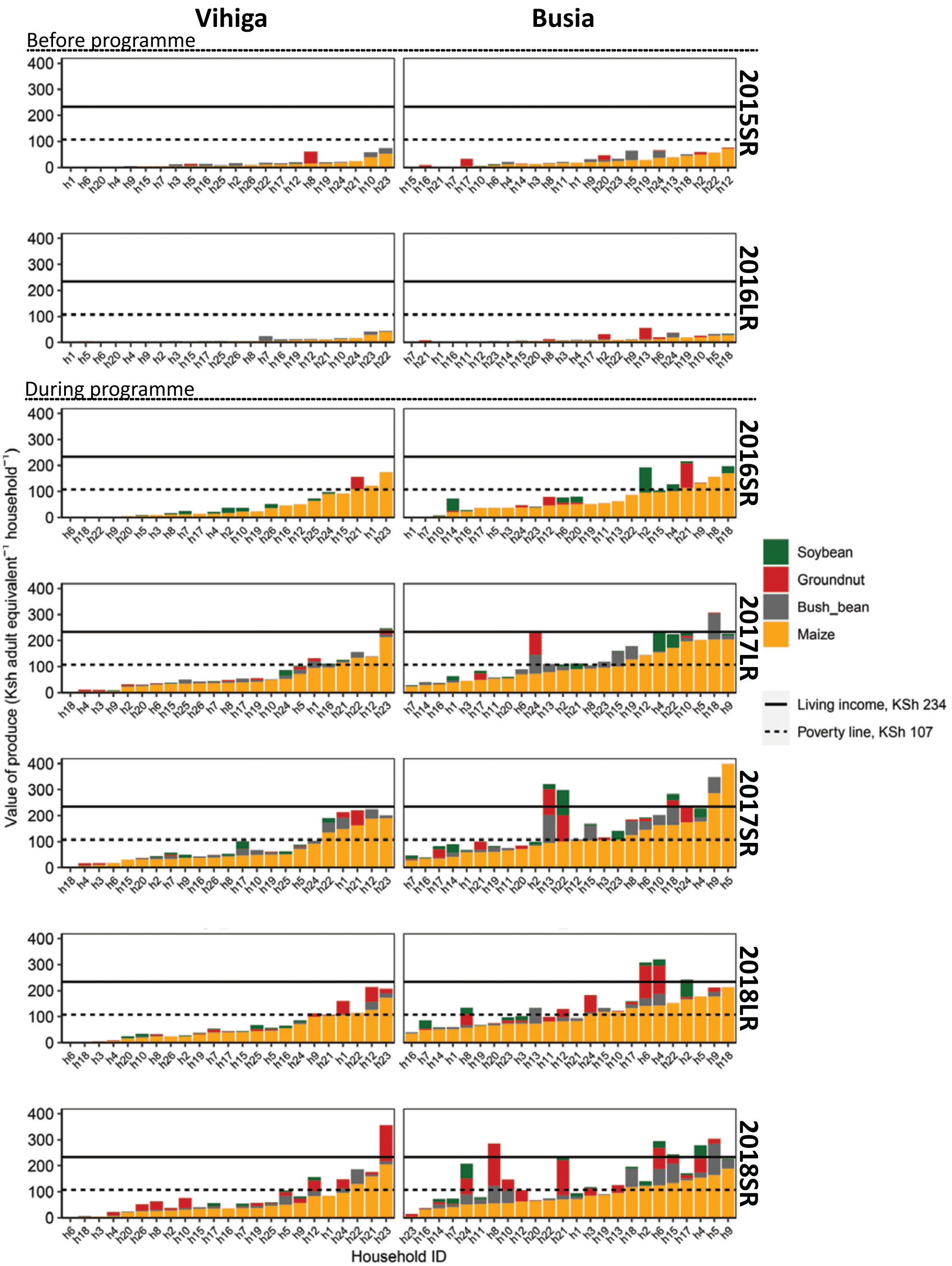

Fig. 3.2: Value of produce in Kenyan Shilling (KSh) per adult equivalent per day for each household. Households were ordered each season based on their value of produce of maize. Household ID's were assigned per location. Seasons 2015SR and 2016LR were before the programme (farmer reported production), seasons 2016SR, 2017LR, 2017SR, 2018LR and 2018SR were during the programme with the voucher available (researcher measured production). SR :short rains cropping season; LR: long rains cropping season.

3.3.4 Value of produce in relation to farm area.

Total value of produce was related to farm area, and the relation was stronger after the start of the voucher intervention (e.g. 2017LR in Fig. 3.4A) than before the voucher was introduced (e.g. 2016LR in Fig. 3.4A). Moreover, with the voucher, the difference in value of produce between households with a small and a large farm area increased (Supplementary materials 3.5). A similar pattern was observed when the value of produce was expressed per adult equivalent per day (Fig. 3.4B), albeit with more variation, resulting from the variation in household size. The number of adult equivalents per household was higher in Busia (at a median of 4.6) than in Vihiga (at a median of 3.2), which reduced the differences between the two locations when expressed per adult equivalent. Some households obtained an above average-value of produce per unit area of land. These households did not necessarily obtain greater yields, but planted almost their whole farm with the four crops that were part of the intervention.

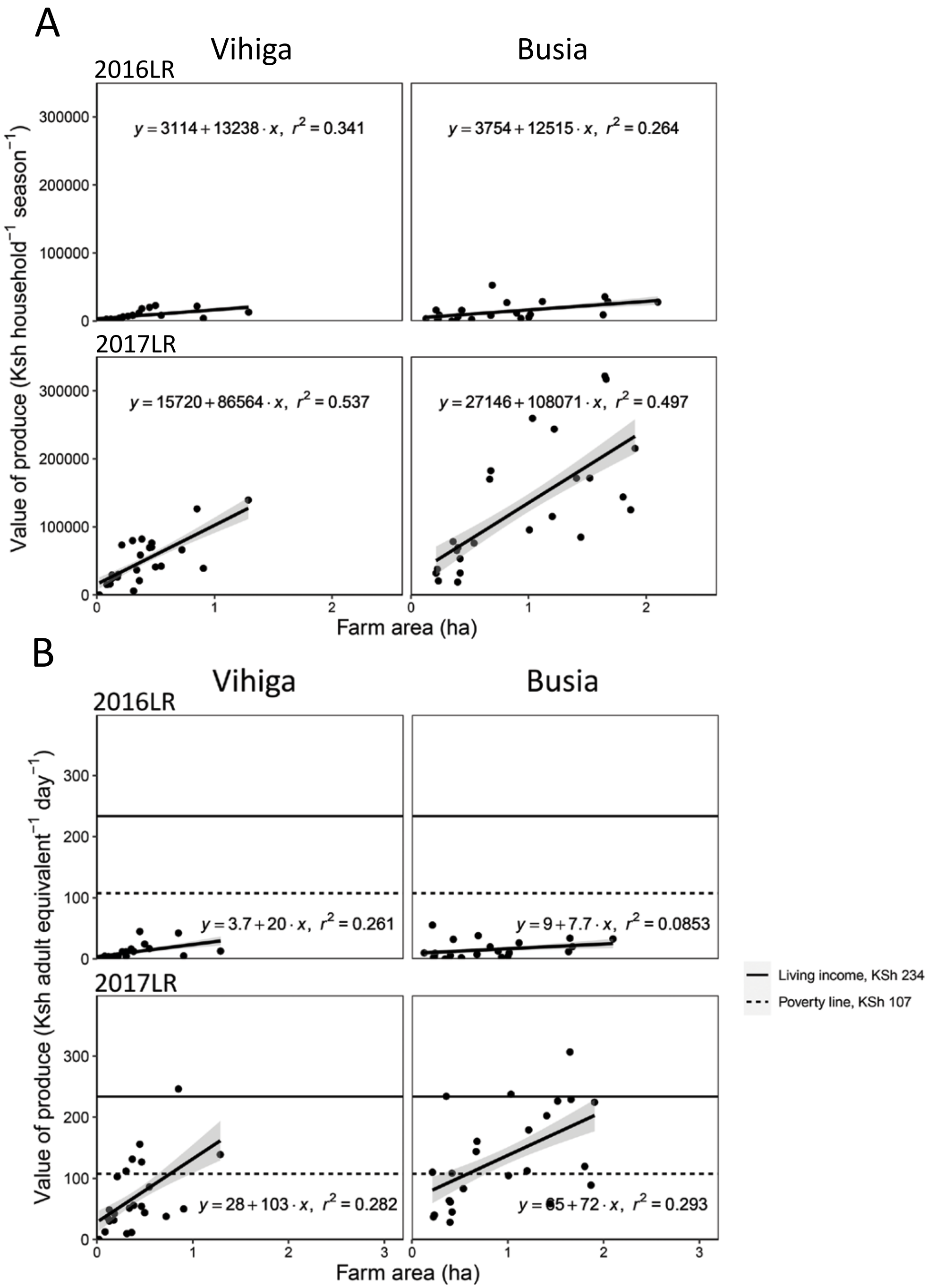

Fig. 3.4: Total value of produce in Kenyan Shilling (KSh) per household per season (A) and the value of produce per adult equivalent per day (B) in relation to farm area during the long rains (LR) cropping season before the programme (2016) and during the programme (2017).

3.4 Discussion

Alleviating resource constraints through providing farmers with an input voucher resulted in an increase of maize yields at farm-level from 16% to 40-50% of the water-limited yield (Fig. 3.1). Yet this large and immediate yield increase lifted only few households out of poverty (Fig. 3.2). Even fewer households obtained a value of produce sufficient to reach a living income in Vihiga. The situation was better in Busia due to the farms being larger in area. With the introduction of the vouchers, land became a more strongly limiting factor for increasing the value of produce (Fig. 3.4). The vouchers stimulated not only the intensification of agriculture by using more inputs, but also extensification, as farmers increased their farm area (Fig. 3.3). However, with a much denser population, Vihiga harboured less options for expansion compared with Busia.

Our results showed that relieving cash constraints for purchase of inputs is a relatively easy measure to strongly increase crop yields. We demonstrate that current available technologies in western Kenya (e.g. varieties, fertilizer practices) are sufficient to reach 50% of the water-limited yield (Fig. 3.1), which was proposed as a goal for reaching food self-sufficiency by 2050 in SSA (van Ittersum et al., 2016). This was achieved at the farm level across farms in an area known for its high diversity within and between farms in terms of soil fertility and yield response (Tittonell et al., 2005a; Vanlauwe et al., 2006). Reaching such a yield target would require substantial institutional changes in addition to the input voucher scheme tested in this study. Indeed, increased production through input subsidies brings a risk of overproduction and deflating prices, as was seen at national level with the Sasakawa Global 2000 programme in Ethiopia (Abate et al., 2015; Spielman et al., 2010). Therefore, it is more effective to provide incentives to increase production as part of a package of policies (Dorward et al., 2008), which also include e.g. price protection, strategic grain reserves and dynamic subsidies that reduce if overproduction is looming or when markets become more functional (Dorward et al., 2007; Koning, 2017). A production target should also consider other trade-offs, such as risks to the environment (Klapwijk et al., 2014).

Providing a USD 100 voucher each season may be expensive for African governments and the mixed results of recent input subsidy schemes in SSA should be considered (Jayne et al., 2018) as theses can shed a light on the effectiveness of such a scheme at scale. The aim of our study was not to assess returns on investment of the voucher. Or findings however show that for about the 25% farms with smallest farm areas in Vihiga, the total value of produce did not outweigh the value of voucher USD 100 input voucher, while for the remaining 75% and all farms in Busia, value of produce did outweigh the voucher (Supplementary materials 3.3). Agricultural production in the United States and Europe has been subsidized for decades with amounts that go beyond the USD 100 voucher per cropping season. As an example, the EU direct income subsidy was about USD 474 ha^{-1} $year^{-1}$, including a re-greening subsidy, in The Netherlands in 2020 (Minstry of Economic Afairs, 2013). On a per hectare and season basis, farmers received on average an income of USD 270 ha^{-1} in Vihiga and USD 118 ha^{-1} in Busia, with the difference due to the difference in farm area. Although this may not be a fair comparison with The Netherlands having a GDP that is 15 times larger than Kenya (The World Bank, 2019a), it indicates the importance that other countries give to keeping agriculture profitable for farmers. In SSA, where agriculture contributes a large part of the economy, e.g. 34% for Kenya in comparison with less than 2% for the Netherlands (The World Bank, 2019b), agricultural subsidy schemes may important as it is such a large part of the economy. Considering the difficult but needed transformation of smallholder agriculture in terms of increasing yields and farmer incomes (Giller, 2020), input subsidies could be part of a wider set of institutional changes that ensure that such a transformation is profitable for smallholder farmers. An option for SSA governments could be to start with initially smaller incentives such as temporary voucher schemes to support adoption of new options for a number of seasons (e.g. new varieties), and/or credit schemes similar to the ones provided by One Acre Fund.

Farm area limited the value of produce of farmers using the input voucher (Fig. 3.4). Production without the voucher was less constrained by farm area, which may imply that intensifying production is currently not profitable and/or not within the reach for smallholder farmers given their current cash constraints, even if they have a larger farm area. Comparison to the poverty line and living income benchmarks illustrated the limited potential of cultivating basic staple crops on small plots in terms of achieving a decent living (Fig. 3.2). This lack of prospects partly explains why smallholder farmers in current systems invest little in inputs and other technologies for increasing farm production and why farmers migrate to cities or other areas, for off-farm opportunities (Crowley and Carter, 2000; Falconnier et al., 2015; Ritzema et al., 2017). Our empirical results on the limitations of small farm areas are in line with Harris and Orr (2014), who calculated household level benefits of technologies tested on farm. Similarly, both Ritzema et al. (2017) and Gassner et al. (2019) showed in their scenario analysis that options for sustainable intensification would mainly benefit households with larger farm areas, while households with small farm areas remain food insecure and have limited financial benefits from such options. Income from farming can be increased by increasing farm areas through land reforms of existing farm land, which would require additional employment opportunities for those moving out of farming (Giller, 2020). Without additional employment opportunities, the ultra-small farms would possibly be better off with a social safety net which does not, or only partly, focus on farming (Gilligan et al., 2009) than with an input voucher.

Farm area increased for more than one-third of participating farmers with the provision of a voucher, even in a densely populated area like Vihiga. Although for some households this led to relatively large increases in value of produce, for none of the households increasing their farm area this led to obtaining a living income. Facilitating secure land tenure arrangements could be an important role for national or local governments to foster the use of land that is currently not in use. This could enable for instance land-owners living elsewhere to rent out their land without the risk of losing their ownership rights, while those who are renting can increase production (Schut and Giller, 2020). In other areas where land is relatively more abundant, such as in Busia, current fallow land can be used to increase farm area, as we found. The use of fallow land in Busia, partly fits in a wider trend in SSA of increasing cultivated land area, resulting in extensification instead of (sustainable) intensification on land currently in use (Giller et al., 2021; Jayne and Sanchez, 2021). However, these trends of extensification are often the result of the increasing smallholder farming population and new groups of large land owners going into farming (Sitko and Jayne, 2014). Cultivated area per farm however, generally decreases in current farming systems due to land fragmentation and populations pressure (Headey and Jayne, 2014; Jayne and Muyanga, 2012). The increase cultivated area per farm that we found may therefore be a specific result of the input voucher.

Additional research is required to assess how a living income from farming could be attained through changes in farm area and/or adjusting the cropping system, e.g. cultivating more profitable crops or reaching higher yield levels. High-value crops could be included in a voucher or subsidy scheme for increased household level income and diversified production. In this study we focussed on the main crops cultivated and those important for food security (e.g. maize, beans). For some households, legumes were an important part of their value of produce, more than maize. Crop diversity also allows crop rotations (c.f. Franke et al., 2018) and benefits household nutrition (de Jager et al., 2019). Other crops like vegetables can be more profitable, but often are much more perishable and management requires more attention than grain crops (Joshi et al., 2006).

Our study was conducted in western Kenya, which is representative of the East African highlands in terms of the bimodal rainfall pattern and deep soils, resulting in a favourable agro-ecological potential compared with many other regions of SSA (Vanlauwe et al., 2013). Most inputs were relatively easily available and to some extent, farmers were accustomed to applying mineral fertiliser and sowing improved varieties. This may be due to a long history of promoting these inputs by the Kenyan government, NGO's and, in recent years, by One Acre Fund. This context favouring input use is quite different from many regions in SSA, including for instance neighbouring Uganda, where little mineral fertiliser is applied to food crops (Sheahan and Barrett, 2017). In such cases where farmers lack experience of fertiliser use (Pincus et al., 2018), it may require more effort to increase farmers' knowledge and encourage uptake through e.g. on-farm demonstrations and learning activities.

The detailed empirical work of this study, including crop yield sampling in all of the fields of the 47 participating farmers, meant that we could not work with a larger sample of farmers. However, the purposeful selection of a diverse group of farmers, following Giller et al. (2011), provides confidence that yields and production results are representative for the smallholder farming systems in western Kenya. Grain yields before the intervention were based on farmer reported production per field while during the intervention they were based on measured crop cuts. The farmer-reported maize yields were in line with reported yields by local counties in the period 2012-2014 at an average 1600 kg ha^{-1} for Vihiga and 1450 kg ha^{-1} for Busia (MoALF, 2015). Farm-level yields obtained during the intervention aligned with yields from earlier field-level experimental work in western Kenya (Njoroge et al., 2017; Vanlauwe et al., 2006).

Our results paint a positive picture of household level financial gains from agriculture. We used ‘value of produce’ as an estimate for income and input costs were not subtracted, as most was provided through the voucher. Including the voucher as a cost, would result in a negative income the for smallest farms (Supplementary materials 3.3). Costs for other inputs besides the voucher inputs were also not included, so that in reality, income from farming would be less. On the other hand we only included the four main crops, leaving out crops like trees, Napier grass and vegetables. These crops were mainly cultivated by the larger farms (not shown) or, in the case of trees, on land unsuitable for arable crops (e.g. rocky outcrops, waterlogged areas). Hence, overall, our results provide a robust picture of the impact of a USD 100 input voucher on household value of produce and limitations by farm area.

3.5 Conclusions

Increasing food demand in SSA, as a result of the burgeoning population, will require substantial changes in farming systems to increase production of basic staple crops. Smallholder farmers, who currently supply most of the national food needs but achieve low yields and mostly live in poverty, will need smart incentives and other support if they are to be part of providing for these future food needs. In this study we tested such an incentive for increasing production. Our results showed that providing a USD 100 input voucher per season increased maize yield from 16% to 40-50% of the water-limited yield, which was insufficient to provide a living income for most farmers. Therefore, in current smallholder farming systems, crop yields are mainly limited by cash constraints at household level and not by technological constraints. Farm area was an important limiting factor for value of produce when input use increased with the introduction of the voucher. For future farming systems therefore, an increase in the farm area per farm is essential to provide smallholder farmers a viable pathway out of poverty. As a consequence, changes will be required such as creating off-farm employment opportunities, social safety nets and possible land reforms to create opportunities for many current farmers that are now ‘hanging in’ on unviable small farms.

Chapter 4

Intensification, extensification, specialization and/or diversification? Farmer responses to an integrated co-learning approach

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Marinus, W., Descheemaeker, K., van de Ven, G.W.J., Vanlauwe, B., Giller, K.E., (submitted). Intensification, extensification, specialization and/or diversification? Farmer responses to an integrated co-learning approach.

Abstract

Sustainable intensification is seen as a key strategy to sustainably increase production and improve livelihoods of smallholder farmers in sub-Saharan Africa. Many of these farmers however, are caught in a poverty trap: a viscious cycle of low productivity and lack of incentives to invest in agricultural inputs. Moving towards sustainable intensification may therefore require incentives such as input subsidies and learning on options for sustainable intensification. Supporting such agricultural developments however, may not always be straight forward as agricultural developments often diverge from desired pathways, e.g. extensification instead of intensification and specialization instead of diversification.

Our overarching aim was therefore to improve the understanding of farmer responses to input subsidies and co-learning, in order to better support future sustainable intensification pathways in smallholder farming. We used a diverse set of indicators to analyse five seasons of detailed farm level data, which was gathered as part of a co-learning programme in western Kenya. The integrated co-learning approach included an input voucher and was compared with a voucher-only approach.

The integrated co-learning approach proved key in facilitating more complex changes in farm management, e.g. diversification through an increase in legume area. Other responses were mainly a result of the input voucher itself. Both groups increased maize yields (intensification) and most households became maize self-sufficient,. An increase in farm and maize areas in combination with relatively low N application rates (risk of soil N mining) however, also pointed at extensification. Value of produce remained below a living income for most households due to the small farm areas. Our results highlight the difficulty of enabling an increase in yields and agricultural production, while also meeting other environmental and economic principles. The diversity of farmer responses and constraints beyond the farm level also underlined the importance of wider socio-economic developments in addition to support of sustainable intensification at farm level.

4.1 Introduction

Livelihoods of smallholder farmers in sub-Saharan Africa (SSA) are under pressure. Many are caught in a poverty trap, a vicious cycle of low productivity and lack of opportunities and incentives to invest in agricultural inputs (Koning, 2017; Tittonell and Giller, 2013). Additionally, constraints such as small farm sizes, limited market access and a changing climate ask for considerable changes in current farming systems (Giller, 2020). Sustainable intensification of farming is seen as a key strategy to enhance rural livelihoods in SSA (Vanlauwe et al., 2014). Sustainable intensification aims to enhance production per unit land, nutrient and labour input, while reducing environmental damage, building resilience and natural capital, and securing environmental services (e.g. Pretty et al., 2011; The Montpellier Panel, 2013). Struik and Kuyper (2017) argue that the concept of sustainable intensification can be used as a "*process of inquiry and analysis*" and discuss how the social and economic dimensions of sustainability can be included. Taking such a broad view enables identification of trade-offs that arise when agricultural systems intensify. Using a diverse set of indicators to describe these trade-offs can inform decision making by society and policy makers (Struik et al., 2014; Struik and Kuyper, 2017).

However, increasing yields through sustainable intensification is challenging in SSA (Schut and Giller, 2020) and alternative pathways are often more apparent. For instance, extensification is currently more common than intensification in many regions of SSA (Baudron et al., 2012; Ollenburger et al., 2016). As continued extensification is associated with soil nutrient mining, intensification would have to reverse this common trend by strongly increasing nutrient inputs (IFAD report/paper), which is challenged by the widespread poverty traps (Koning, 2017; Tittonell and Giller, 2013). Current trends show an increase in the area under maize (Santpoort, 2020; van Loon et al., 2019), which historically has been linked to increasing population, increasing food requirements and urbanization (Smale and Jayne, 2003) and, resulting in land pressure (Crowley and Carter, 2000). Although specialization towards maize allows the production of sufficient food, diversified cropping systems would be more sustainable in terms of income, nutrition, crop yields and risk spreading (Vanlauwe et al., 2019). Hence, identification of constraints and opportunities is essential to support pathways towards sustainable intensification, including both diversification and intensification.

Setting sustainable intensification as an overall goal for smallholder farming systems results in multiple subsidiary goals, e.g. increased yields, desired N use efficiencies, food self-sufficiency at household and national level. Attaining all goals simultaneously may be virtually impossible, especially because farmers follow their own objectives and prioritize some goals over others, leading to trade-offs (Klapwijk et al., 2014; Vanlauwe and Dobermann, 2020). Some goals will require time before they can be attained (Vanlauwe et al., 2010) and outcomes may differ between seasons, requiring assessment over multiple seasons, which is rarely done (Smith et al., 2017). Measuring progress towards the multiple goals of sustainable intensification requires a multi-criteria assessment of indicators associated with the principles of sustainability. Using a framework of principles and criteria warrants transparency and a justified selection of indicators (Florin et al., 2012). According to Florin et al. (2012, p.109), "*Principles are the overarching ('universal') attributes of a system. Criteria are the rules that govern judgement on outcomes from the system and indicators are variables that assess or measure compliance with criteria*". Criteria can also help to decide upon benchmarks to judge whether a goal is reached. Within sustainable intensification of smallholder farming systems, criteria, indicators and benchmarks need to address different levels, including the field, farm and household level. Also at national level, increasing yields to a certain threshold is required to attain food self-sufficiency, while at farm level maize self-sufficiency is an important indicator that often fits with farmers' objectives.

The investments in inputs required for sustainable intensification are beyond the reach of most smallholder farmers (Vanlauwe et al., 2010) and need incentives such as input subsidies. In the past two decades several fertiliser and seed subsidy programmes were (re-)initiated by African governments (Jayne et al., 2018). In addition, social enterprises, such as One Acre Fund (www.oneacrefund.org), appeared which provide inputs though credit schemes to smallholder farmers. Increased input use, however, also requires new knowledge (Jayne and Sanchez, 2021). In a large scale subsidy scheme in Malawi, the limited extension provided by the government was seen as a possible cause for N use efficiencies to remain low (Dorward et al., 2008). Co-learning, an iterative learning framework involving farmers and researchers or extension workers, has proven to be successful in developing contextualized knowledge (Descheemaeker et al., 2019). Co-learning may therefore be useful to resolve emerging questions related to increased input use. We developed an integrated co-learning approach (Marinus et al., 2021), which aimed to sustainably increase farm level production by fostering increased input use through the provision of a voucher, in combination with knowledge co-creation. In this paper we apply a multi-criteria assessment over five seasons to analyse the outcomes of the integrated co-learning approach in relation to different pathways towards sustainable intensification.

Our overarching aim was to improve the understanding of farmer responses to input subsidies and new knowledge, in order to better support sustainable intensification pathways in smallholder farming. This materialized in the following objectives to: 1) Assess the effect of co-learning on farmers' decisions and management outcomes compared to providing only a voucher for inputs; 2) Analyse the above effects in terms of criteria and indicators that relate to sustainable intensification; 3) Describe farmers' responses in terms of pathways of intensification, extensification, specialization and/or diversification resulting from the integrated co-learning approach.

4.2 Methodology

4.2.1 The integrated co-learning approach

We applied an integrated co-learning approach from August 2016 until July 2018, as described in detail by Marinus et al. (2021). The approach combined four complementary elements: input vouchers, an iterative learning process, common grounds for communication, and complementary knowledge. An input voucher of USD 100 per season was provided each season to each farming household which was aimed to alleviate resource constraints and increase input use by participating farmers. Inputs for maize, groundnut, soybean, common bean and sorghum production and for dairy were made available to the farmers for purchase using the voucher. Most of these inputs were offered from the start, while some (e.g. groundnut and (short duration) common bean seed and IR-treated maize seed against striga) were added during the programme in response to feedback from the farmers. This feedback was central to an iterative learning process in which a co-learning workshop prior to each cropping season played a pivotal role. The focus of the workshops evolved over time based both on questions and feedback from farmers during the season as well as topics identified by the researchers. Discussion topics during the workshops included the judicious use of mineral fertilisers and the cultivation of alternative crops such as legumes. Researchers monitored the farmers' responses through a mid-season field survey, yield data collection and an evaluation interview at the end of each season with each farmer individually (see Marinus et al., (2021) for further details).

4.2.2 Research set-up

The integrated co-learning approach was tested in two locations, Vihiga and Busia county in western Kenya. Vihiga is one of the most densely populated rural areas in SSA with 1050 people km^{-2}, with small farm sizes of <0.5 ha. Busia is more moderately populated with 530 people km^{-2}, and somewhat larger farms of about 1.0 ha (Jaetzold et al., 2005; KNBS, 2019). Both locations receive a rainfall of 1800-2000 mm year^{-1} in a have a bi-modal rainfall pattern (Jaetzold et al., 2005), with the long rains (LR) cropping season from March until June and the short rains (SR) cropping season from September until November. Activities started in the SR season of 2016 and continued for five seasons until the SR season of 2018.

In each county, Vihiga and Busia, two sub-locations were selected and in each of these locations 11-12 farmers were chosen. Farmers in one sub-location formed the co-learning group while a comparison group was formed in the other sub-location. The sub-locations were selected to have similar farming systems, yet be sufficiently far apart to avoid spill-over effects. All farmers in the co-learning group received a voucher and took part in the co-learning activities. Those in the comparison group received only the seasonal input voucher. Although the mid-season field monitoring survey and yield measurements were done on all farms, comparison farmers did not take part in evaluation interviews or discussions about farm management. The mid-season field monitoring survey included a visit by researchers to each field including fields that were newly added during the programme, to record the crops cultivated and the percentage intercropping. In addition, the farmer was asked about input use, planting dates and other crop management. Field sizes were measured using a hand-held GPS before the start of the programme in June 2016. Small fields with sides less than 20 m were measured by hand. Yield measurements were done in two 4 × 4 m (16 m^2) quadrats in all fields containing maize, groundnut, soybean and/or common bean. These crops together made up about 60-70% of the total cultivated area per farm. Fresh cob (maize) and pod (legumes) yields were measured in the field, with one sub-sample per quadrant to determine dry weight, using oven drying. Dry weights were calculated back to a standardized moisture content of 14% and the grain yield (kg ha^{-1}) per field was calculated based on the average of the two quadrats. The detailed monitoring and measurement campaign during five seasons ensured a comprehensive assessment of possible changes in farm management over time. However, the limited number of farmers per sub-location precluded a formal statistical analysis.

4.2.3 The indicator framework: principles, criteria and indicators

We used a multi-criteria assessment to analyse the farmers' decisions and management outcomes of the integrated co-learning programme. Indicators were selected using principles and criteria (Table 4.1). By assessing these indicators over five seasons, we also evaluated the evolution in indicator values over time, which we interpreted as an indication for a pathway (Table 4.1). We identified four principles of sustainable intensification of smallholder systems: productivity, food self-sufficiency, environment and economics. For each principle, one to four criteria and indicators were included. The yield-related indicators focused on maize which was the most important crop in terms of food and sale. Nearly all households cultivated maize every season, enabling a comparison between households and over time.

Apart from presenting indicator values per household, we also present them in a spider web diagram as averages for comparison and co-learning farmers per location. Indicator values for the spider web diagram were scaled using a zero to ten score based on the benchmarks for each indicator, with a larger score indicating a more sustainable situation (Table 4.1).

4.2.3.1 Productivity

Yield and production

Maize grain yield (kg ha^{-1}) was measured in all maize fields, both monocropped and intercropped, as described above. A farm-level, weighted average maize grain yield was then calculated based on the area of each maize field. The benchmark for yield was 50% of the season-specific, water-limited yield in western Kenya, which can be seen as a possible future yield target to attain national or regional food self-sufficiency (van Ittersum et al., 2016). The water-limited yields for the long and the short rains cropping seasons were 12.5 Mg ha^{-1} and

Table 4.1: Sustainable intensification indicators organised according to the relevant principle (in italics) and criteria. The third column identifies other possible principles under which an indicator may also fit. Where relevant, possible pathways for agricultural systems are named. Benchmarks were determined per indicator and a score from zero to ten was applied, whereby a larger score indicates a more sustainable situation. References are given for specific benchmarks where applicable.

Principles and criteria	Indicators	Related to other principle	Possible pathways	Unit	Benchmarks and scoring 0	10	References
Productivity							
Reducing yield gaps	- Maize yield		Intensification/ extensification	kg ha^{-1}, relative to Yw[1]	0% Yw	>= 50% Yw	(van Ittersum et al., 2016)
Feeding the household throughout the year	- Maize production	Food self-suf., economics	-	kg $household^{-1}$			
Food self-sufficiency							
Feeding the household throughout the year	- Maize self-sufficiency		-	fraction	0	>= 2	
Environment							
Avoiding N losses as well as soil N mining	- N use efficiency maize		Intensification/ extensification	%	<= 50 >= 100	>= 70 <= 90	(Brentrup and Palliere 2010; EU Nitrogen Expert Panel 2015)
	- N surplus maize		Intensification/ extensification	kg N ha^{-1}	0 >= 120	>= 50 <= 80	(Brentrup and Palliere 2010; EU Nitrogen Expert Panel 2015)
Ensuring rotation and diversification	- Crop area: maize	Economics	Intensification/ extensification	ha, % of farm area	>= 75%	<= 25%	
	- Crop area: legumes	Economics	Diversification/ specialization	% of farm area	0%	>= 30%	
Economics							
Allowing a decent living	- Value of produce per crop		Diversification/ specialization	Ksh adult $equivalent^{-1}$ day^{-1}	0	>=234 living income	(Anker and Anker, 2017)

[1] water-limited yield (Yw)

4

8.0 Mg ha^{-1} respectively (GYGA, 2020). Maize production at farm level (kg) was calculated based on maize yield and maize area.

4.2.3.2 Food self-sufficiency

Maize self-sufficiency

Maize self-sufficiency at household level (-) was calculated as the total maize production at farm level per season (kg) divided by the maize requirements per household per season (kg). The seasonal maize requirement was calculated from the annual requirement multiplied with the proportional contribution of seasonal maize production to the annual production. The annual household requirements per household were calculated based on the number of adult male equivalents (AME) per household and the energy requirements of an active male, 2500 kcal day^{-1} (FAO/WHO/UNU, 2001). The number of AMEs per household was based on the family composition during the 2018SR, whereby a female was equivalent to 0.82 AME and children (0-18 years) 0.75 AME (FAO/WHO/UNU, 2001). The maize requirements per AME were 260 kg AME^{-1} year^{-1}, based on an energy content of maize grain of 3500 kcal kg^{-1} (Lukmanji et al., 2008).

4.2.3.3 Environment

Nitrogen use efficiency and N surplus

Nitrogen (N) use efficiency of maize was calculated at farm level per season: the total N outputs in maize grain (kg N ha^{-1}) divided by the N inputs on all fields with maize (kg N ha^{-1}). N output was calculated using the weighted average maize grain yield per farm and a fixed N content in maize grain of 1.54% (Njoroge, 2019). A farm level weighted average for N inputs was calculated based on the mineral fertiliser used per field, as reported in the monitoring survey. N use efficiency was analysed using the framework developed by the EU Nitrogen Expert Panel (2015), using a minimum and a maximum N use efficiency of 50% and 90% respectively and a maximum N surplus of 80 kg N ha^{-1}. A N use efficiency below 50% and/or a N surplus of 80 kg N ha^{-1} indicate a high risk of N losses to the environment, while N use efficiencies higher than 90% indicate a high risk of soil mining. The framework also includes a general benchmark for desired output of 80 kg N ha^{-1}. We adjusted this benchmark to reflect the output from 50% of the water-limited yield, equivalent to a N output of 83 and 53 kg N ha^{-1} for the long and the short rains seasons.

Crop area of maize and legumes

Assessing crop area in smallholder farming is not straightforward as crops are commonly intercropped: e.g. maize is often intercropped with legumes such as common bean or soybean. We therefore assessed crop area based on two indicators. Cultivated area per crop (ha) was calculated as the sum of the areas of all fields containing that crop and was used to calculate yields. The percentage farm area per crop (%) was calculated using the estimated percentage intercropping and field area. The percentage farm area per crop was used to compare the areas of maize, common bean, groundnut and soybean among households and groups.

4.2.3.4 Economics

Value of produce per crop

Value of produce per crop was calculated for maize, common bean, groundnut and soybean based on the total production per crop per season and the median crop price for 2018. Median prices were obtained through a weekly market survey after pooling the data from both sites as there were limited differences. Value of produce was expressed per adult equivalent per day based on the household composition in 2018 and season length. Season length for the long rains season was 223 days and 142 days for the short rains season. Input cost were not considered as these were largely paid for through the voucher and therefore free of charge for the households. The value of produce calculated therefore paints a relatively optimistic picture and does not reflect profitability of the farm. As benchmarks, we use the poverty line for Kenya (World Bank, 2015) and the living income for rural Kenya (Anker and Anker, 2017). Both were corrected for inflation, using 2018 as reference year, which was the same year as for the crop prices. Both the poverty line and the living income were expressed per adult equivalent per day, following OECD (2011) and Van de Ven et al. (2020).

4.3 Results

4.3.1 Maize yield and production

Median yields were around 16% of the water-limited yield before the programme (not shown) and strongly increased to almost 50% of the water-limited yield for most households from the first season of the programme onwards. Some farms even reached 80% of the water-limited yield in some seasons (Fig. 4.1). Also the households with the lowest maize yields in the first season (2016SR), obtained higher maize yields in later seasons (Supplementary materials 4.1). Furthermore, households with better maize yields the first season (2016SR) maintained good yields in later seasons. The cultivated area of maize did not influence the maize yield, except in the 2017LR and 2018LR cropping seasons in Busia, where the maize yields tended to be greater for households that had a larger area of maize than for those with a smaller area. There were no differences in maize yields between the comparison and co-learning farmers, nor between Vihiga and Busia.

Households increased their cultivated area under maize during the programme, resulting in increased total maize production per household (Fig. 4.1, Supplementary materials 4.2). This trend was observed irrespective of the initial cultivated area of maize (see also Supplementary materials 4.2).

4.3.2 Maize self-sufficiency and maize area

Most households became maize self-sufficient as a result of the programme, independent of whether they were part of the comparison or co-learning group (Fig. 4.2). Increases in maize area from the second season onwards resulted in a marked improvement in maize self-sufficiency for those households in Vihiga which were not yet maize self-sufficient in the first season. Maize self-sufficiency was achieved by the households in Busia far more often than in Vihiga, due to the larger areas cropped with maize. Some households produced up to six times what they required for maize self-sufficiency. In Busia, larger maize self-sufficiency was associated with smaller fractions of their farm area being dedicated to maize (Fig. 4.2). Households with larger farms, whilst planting a smaller fraction with maize, cultivated a larger area of maize than farmers with smaller farms, who tended to plant maize in nearly all of their fields if their farm was less than 0.4 ha (Fig. 4.3). This critical area of 0.4 ha is roughly needed to produce twice what is required by typical households, thus indicating farmers' priority to attain food self-sufficiency. Maize self-sufficiency and the good market for maize, albeit at low price, were named by farmers as reasons to grow maize in evaluation interviews.

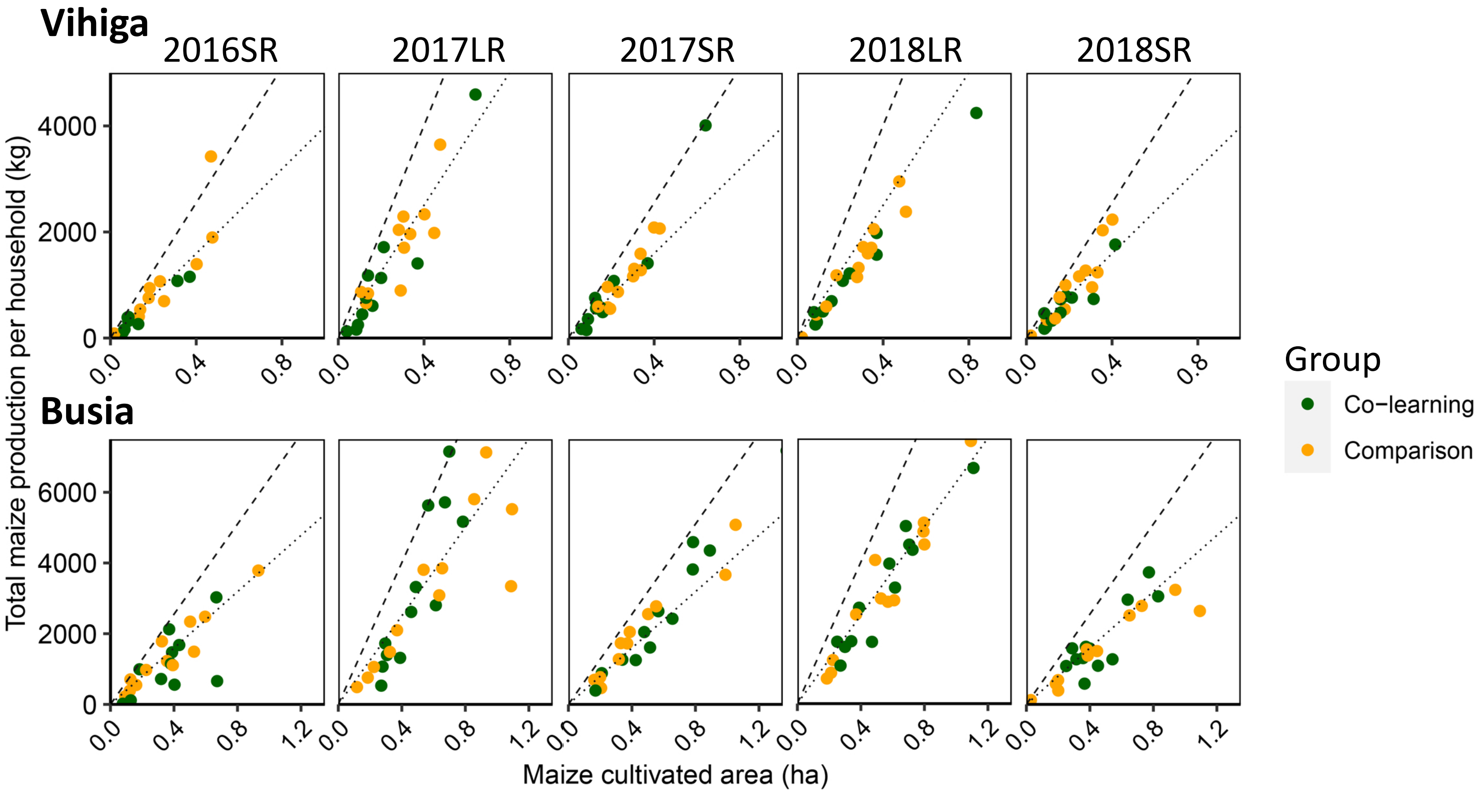

Fig. 4.1: Total maize production per household in relation to the maize cultivated area per household. The grey dotted line indicates a maize grain yield equivalent to 50% of the water-limited yield, 4000 kg ha^{-1} for the short rains (SR) and 6300 kg ha^{-1} for the long rains (LR) cropping season. The dashed line indicates a maize grain yield equivalent to 80% of the water-limited yield, 6400 kg ha^{-1} for the short rains (SR) and 10000 kg ha^{-1} for the long rains (LR) cropping season.

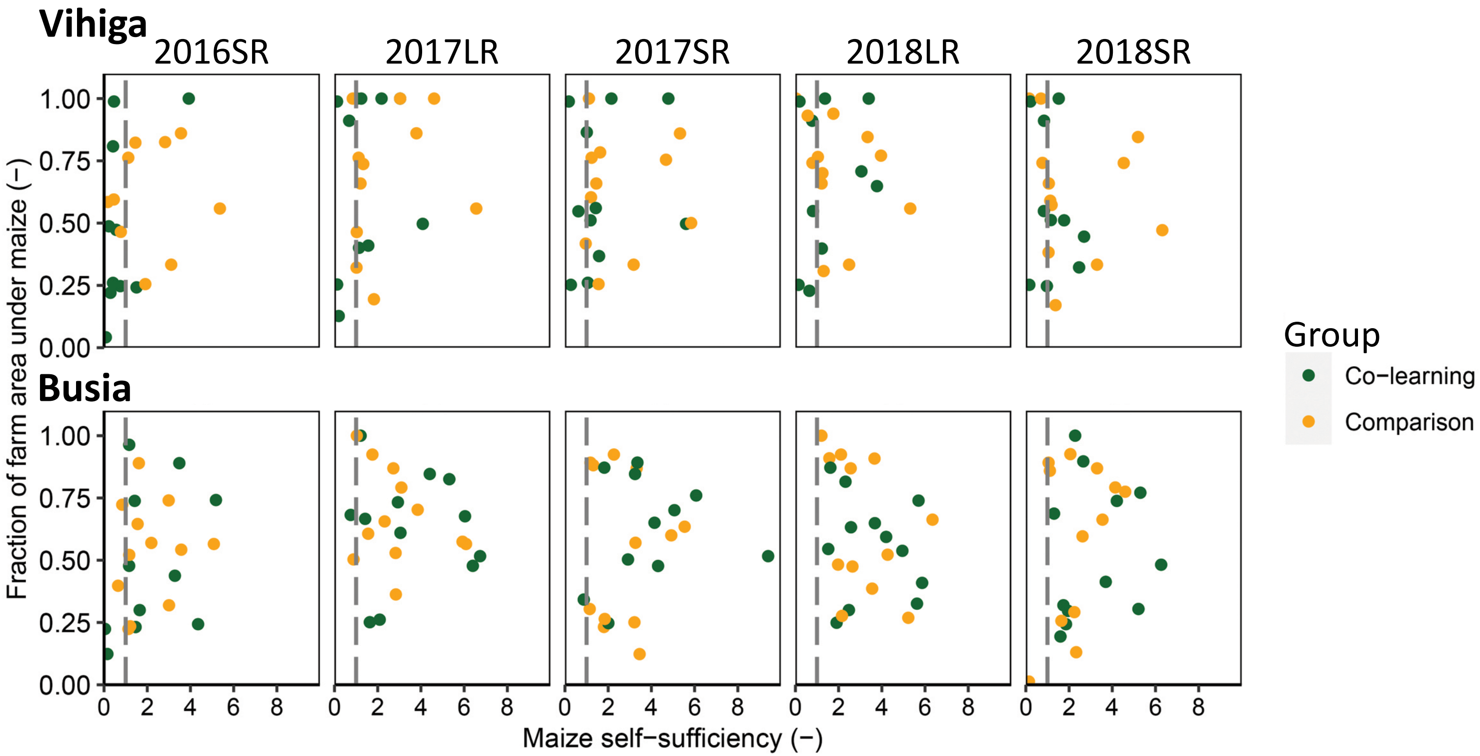

Fig. 4.2: Fraction of farm area under maize in relation to maize self-sufficiency per season. A maize self-sufficiency ratio of one (dashed line) means that a household is maize self-sufficient. The fraction of farm area under maize is not corrected for intercropping.

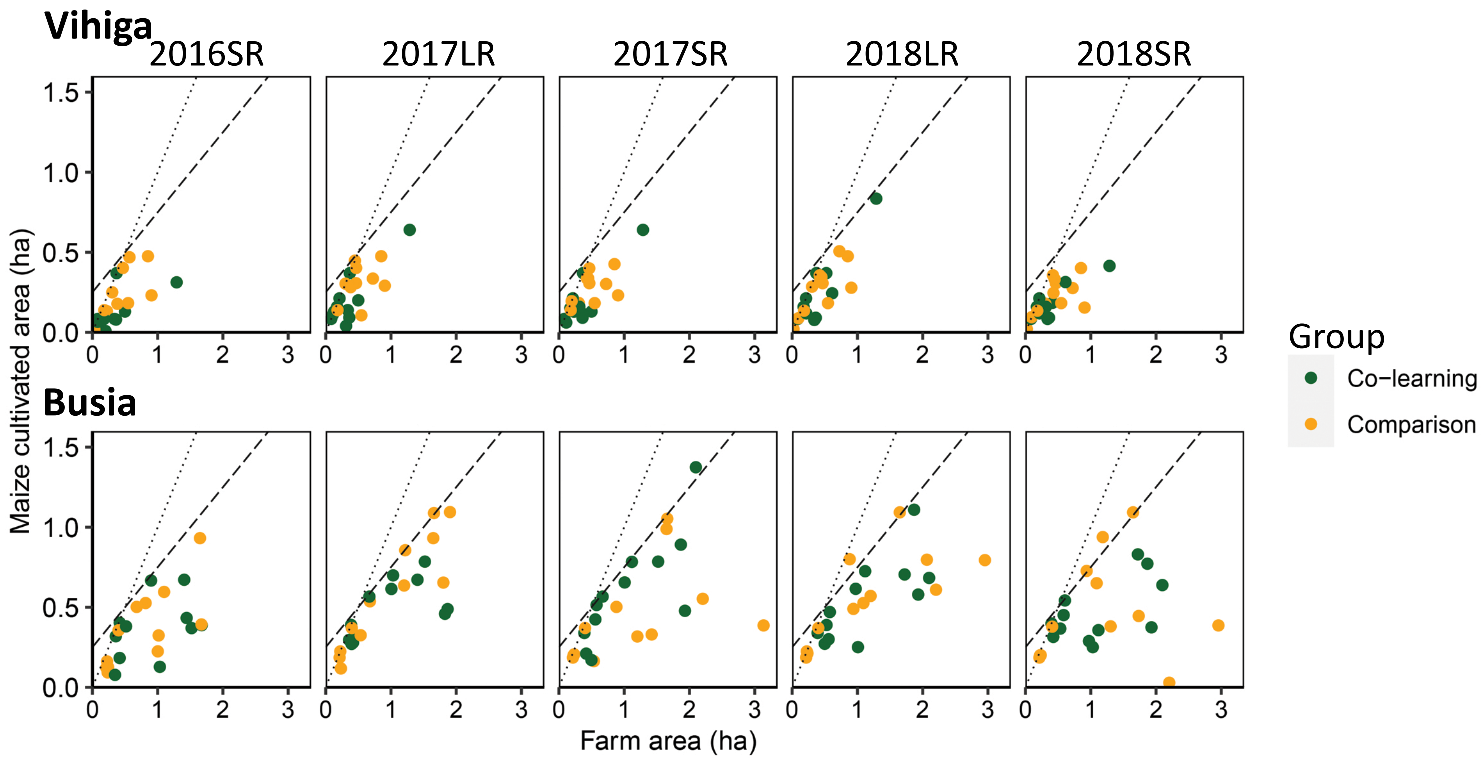

Fig. 4.3: Maize cultivated area per farm in relation to farm area. The dotted line is a 1:1 line, indicating that all fields of the farm contain maize. The maize area is not corrected for intercropping. The dashed line is ‘hand-drawn’ boundary line intercepting with the dotted line at a farm area of 0.4 ha.

4.3.3 Nitrogen use and nitrogen use efficiency

There was a clear negative relation between N application rate and maize area in both Vihiga and Busia (Fig. 4.4). High N application rates (> 120 kg N ha^{-1}) were found in farms with a small maize area (<0.2 ha) and were largest in the first season (2016SR). Especially the co-learning farmers in Vihiga applied high rates, which was attributed to their extremely small cultivated areas. With an increased maize area from the second season onwards, their N application rates reduced but remained high at around 120 kg N ha^{-1}. Farmers with a larger maize area tended to distribute the fertilizers over the larger area, resulting in lower application rates (40-50 kg N ha^{-1}). This relation between N application rate and farm area seemed partly related to the size of the input voucher, which appeared to limit total N use per farm. A common choice was to use 60% of the voucher to buy a 50 kg bag of DAP and a 50 kg bag of CAN, adding up to 23 kg of N which was the common maximum N use per farm across the maize fields (Supplementary materials 4.3). Some farmers with a larger maize area, mainly in Busia, bought limited amounts of additional mineral fertiliser, resulting in moderate fertilizer N application rates of around 50 kg N ha^{-1}, while in the co-learning workshops, application rates of 80-120 kg N ha^{-1} were advised. Application rates were not different between comparison and co-learning farmers.

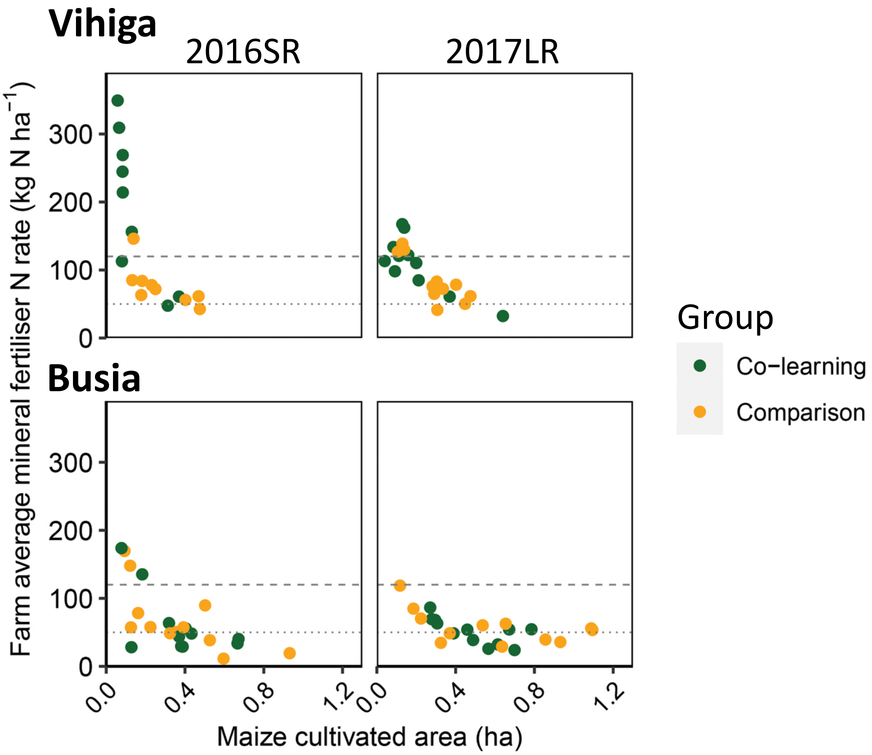

Fig. 4.4: Average mineral N rate applied to maize fields in relation to the area cropped with maize per farm in 2016SR and 2017LR seasons. The grey dotted line indicates an application rate of 50 kg N ha^{-1} and the dashed line 120 kg N ha^{-1}.

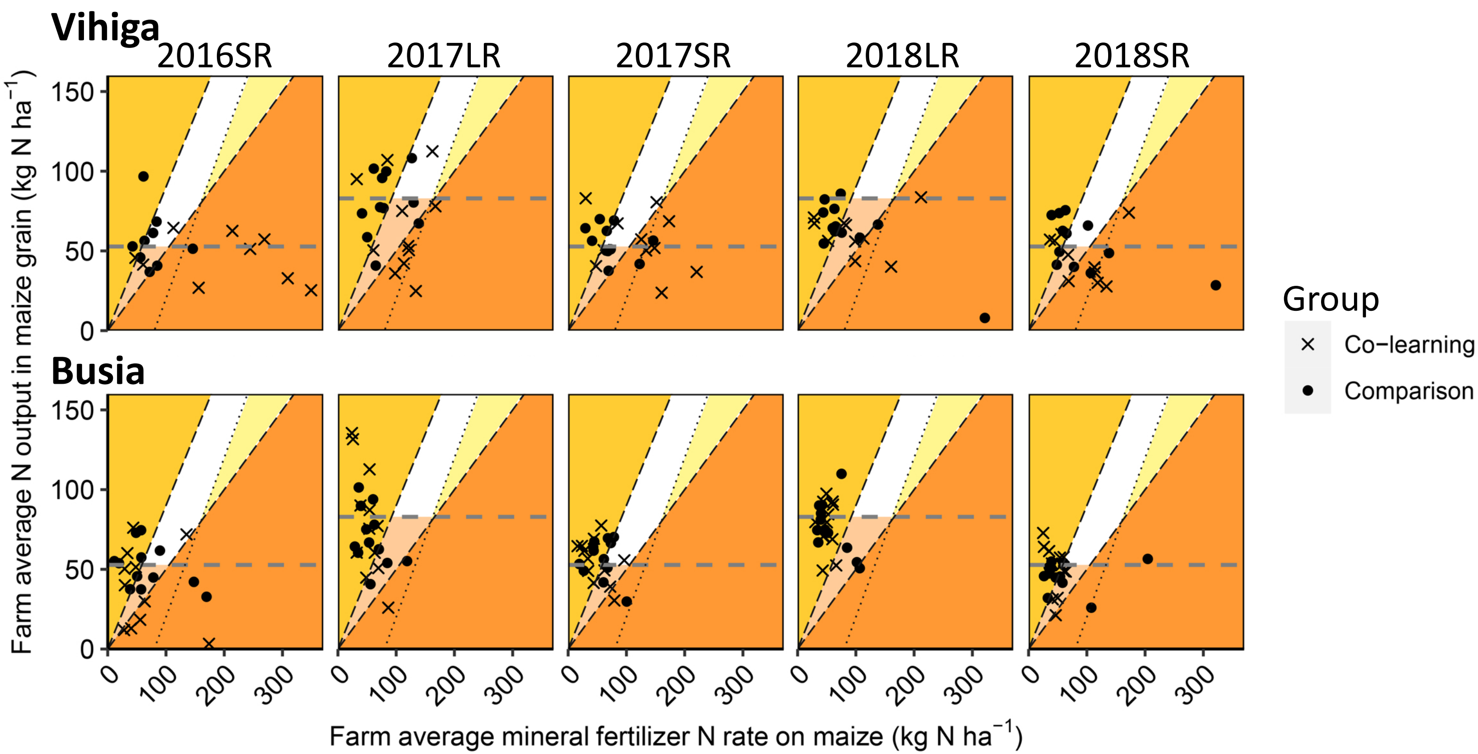

Fig. 4.5: Farm level N outputs in maize grain in relation to N inputs on maize, based on the EU Nitrogen Expert Panel (2015) analysis method. The upper and the lower diagonal lines with a y-intercept of zero indicate a N use efficiency of 90% and 50% respectively. An N use efficiency above 90% indicates a risk of soil N mining, while an N use efficiency below 50% indicates a risk of N losses to the environment. The dotted diagonal line indicates a N surplus of 80 kg N ha^{-1}, which, if exceeded, indicates a risk of N losses to the environment. The horizontal dashed line indicates a N output that is equivalent to 50% of the water-limited grain yield per season, 83 kg N ha^{-1} for the long rains and 53 kg N ha^{-1} for the short rains. The white area indicates the desired range of efficiencies and output.

Only few farms across sites and seasons were within the desired range of N use efficiency (Fig. 4.5). Too high N use efficiencies (>90%), indicating soil mining, were found for most of the farms in Busia, during all five seasons, and for about half of the farms in Vihiga from the second season onwards. These high N use efficiencies were obtained through yields that were close to 50% of the water-limited yield. Too low N use efficiencies (<50%) and too high N surpluses (>80 kg N ha^{-1}) were mainly found in Vihiga (Fig. 4.5), especially in the first season, where large amounts of N-based fertilisers were applied on small maize areas (<0.2 ha). This problem reduced from the second season onwards when the cultivated area of maize increased (Fig. 4.5).

4.3.4 Crop area: specialization and diversification

The fraction of the farm area cropped with maize increased in the first two seasons, whereas that with legumes increased in later seasons. Co-learning farmers planted a larger fraction of farm area with groundnut and soybean in the last two seasons (2018LR and 2018SR) than the comparison farmers (Supplementary materials 4.4 and 4.5). This difference was larger during the long rain cropping season, which is locally seen as the main season for maize. The main season for legumes differed among households, whereby some households cultivated legumes mainly during the long rains and others mainly during the short rains. Small farms tended to grow a larger fraction of the farm area with legumes than larger farms. In evaluation interviews, farmers with larger farms noted labour constraints for cultivating legumes as their main reason for dedicating only a limited area to legumes. In Vihiga legumes were mainly intercropped with maize.

After increasing in the first seasons, the fraction of farm area with maize decreased in the last season (2018SR, Supplementary materials 4.5). The initial increases were realized both by replacing other crops (cassava, sorghum) and by using additional land, e.g. by renting in land and using land that was previously fallow (not shown). Most farmers who decreased their maize area had a relatively large maize area. They reported maize self-sufficiency and low maize prices as main reasons for the decrease. Maize was replaced by groundnut and by leaving land fallow.

4.3.5 Value of produce of crops

Maize contributed most to the total value of produce for most households (Fig. 4.6), as a result of the large fraction of farm area planted with maize. However, for some households, legumes contributed two to three times more tot total value of produce than maize, because of their larger legume area fraction combined with relatively good legume yields (not shown). The expanding areas of legumes also explains why the value of produce of legumes became more important for co-learning farmers than comparison farmers in the last two seasons. In particular groundnut became important, contributing 14% and 8% to total value of produce for co-learning farmers in Vihiga and Busia in 2018LR. For comparison farmers this was 1% in Vihiga and 0% in Busia in 2018LR. Soybean was mainly valued as option to reduce striga

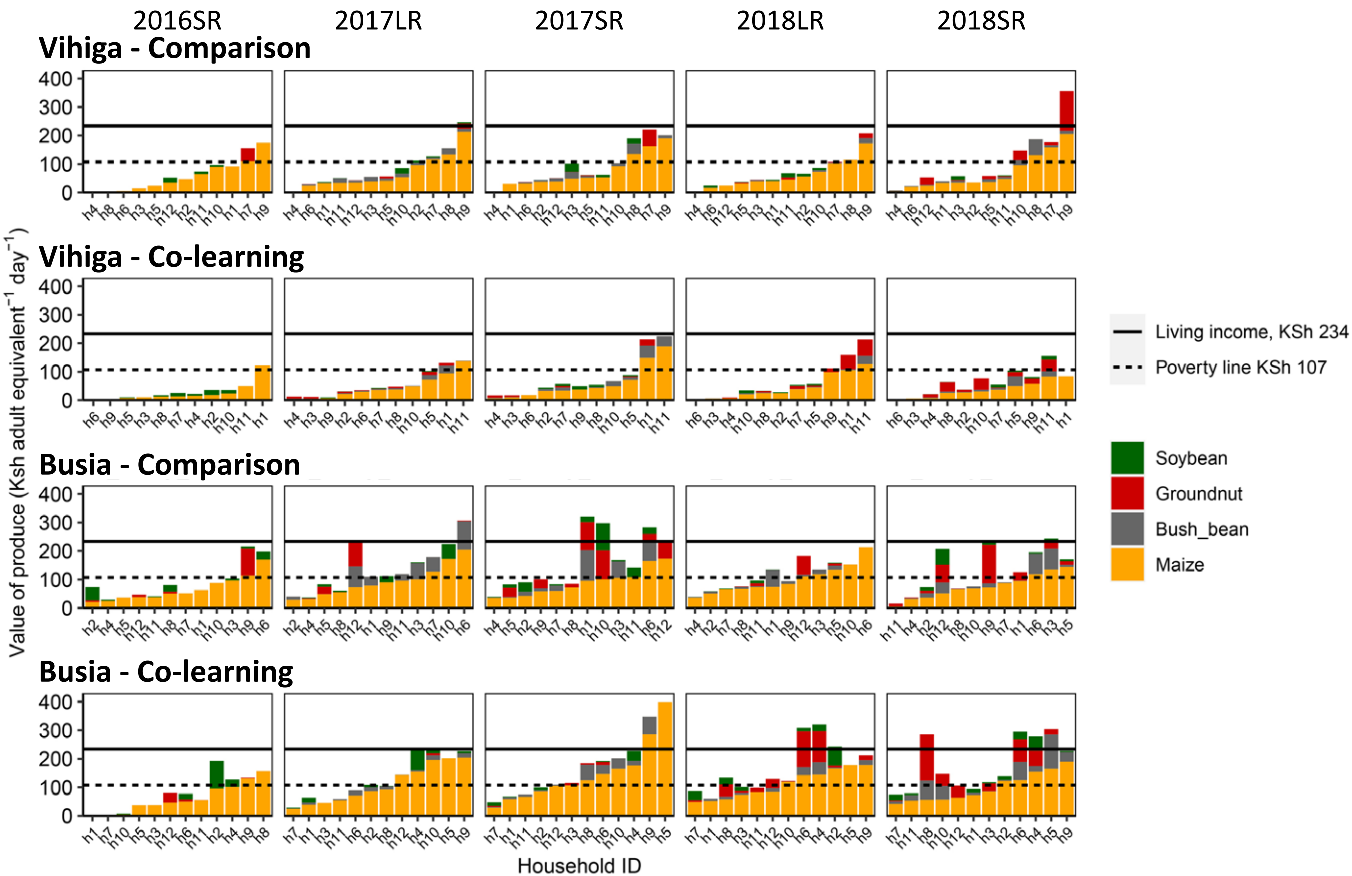

Fig. 4.6: Value of produce for soybean, groundnut, common bean and maize in Kenyan Shilling (KSh) per adult equivalent per day for each household. Households were ordered each season per location for their value of produce of maize. Household ID's were assigned per location. SR stands for short rains cropping season and LR for long rains cropping season.

infestation and less important for its selling value.

Only one household in Vihiga obtained a value of produce that was equivalent to achieving a living income in two of the seasons (Fig. 4.6). In Busia, slightly more households in both groups obtained a living income, which was mainly related to the larger farm area compared with Vihiga. The total value of produce was equivalent to the poverty line for a few households per group in Vihiga and for about one third of the households in Busia.

4.3.6 Indications of pathways for sustainable intensification

Co-learning farmers, both in Vihiga and Busia scored less for a range of indicators (maize yield, maize self-sufficiency, value of produce) at the start in 2016SR than the comparison group farmers (Fig. 4.7). In 2018SR these differences had faded and in Vihiga co-learning farmers scored better in terms of legume area while in Busia co-learning farmers scored better for maize self-sufficiency, maize area, N use efficiency and value of produce, than comparison farmers.

Poor outcomes (score <5) were found for N surplus and N use efficiency across sites and seasons. Value of produce remained poor in Vihiga while scoring better in Busia, especially at the end of the programme (Fig. 4.7). Larger farm areas in Busia were the main reason for higher scores in value of produce and maize self-sufficiency compared with Vihiga.

We detected signs for different pathways simultaneously. Increased maize yields pointed towards the pathway of intensification. Low scores for N use efficiency and N surplus however, mainly due to relatively low N inputs in combination with high yields, also point toward the pathway of extensification as these yields seemed to be based on soil N mining, as also shown in Fig. 4.5. The increases in maize cultivated area (Fig. 4.1), in combination with low N application rates (Fig. 4.3), also pointed towards extensification. The increased cultivated area with maize can also be seen as specialization. Increased legume area and production of co-learning farmers pointed towards the pathway of diversification (Fig. 4.6).

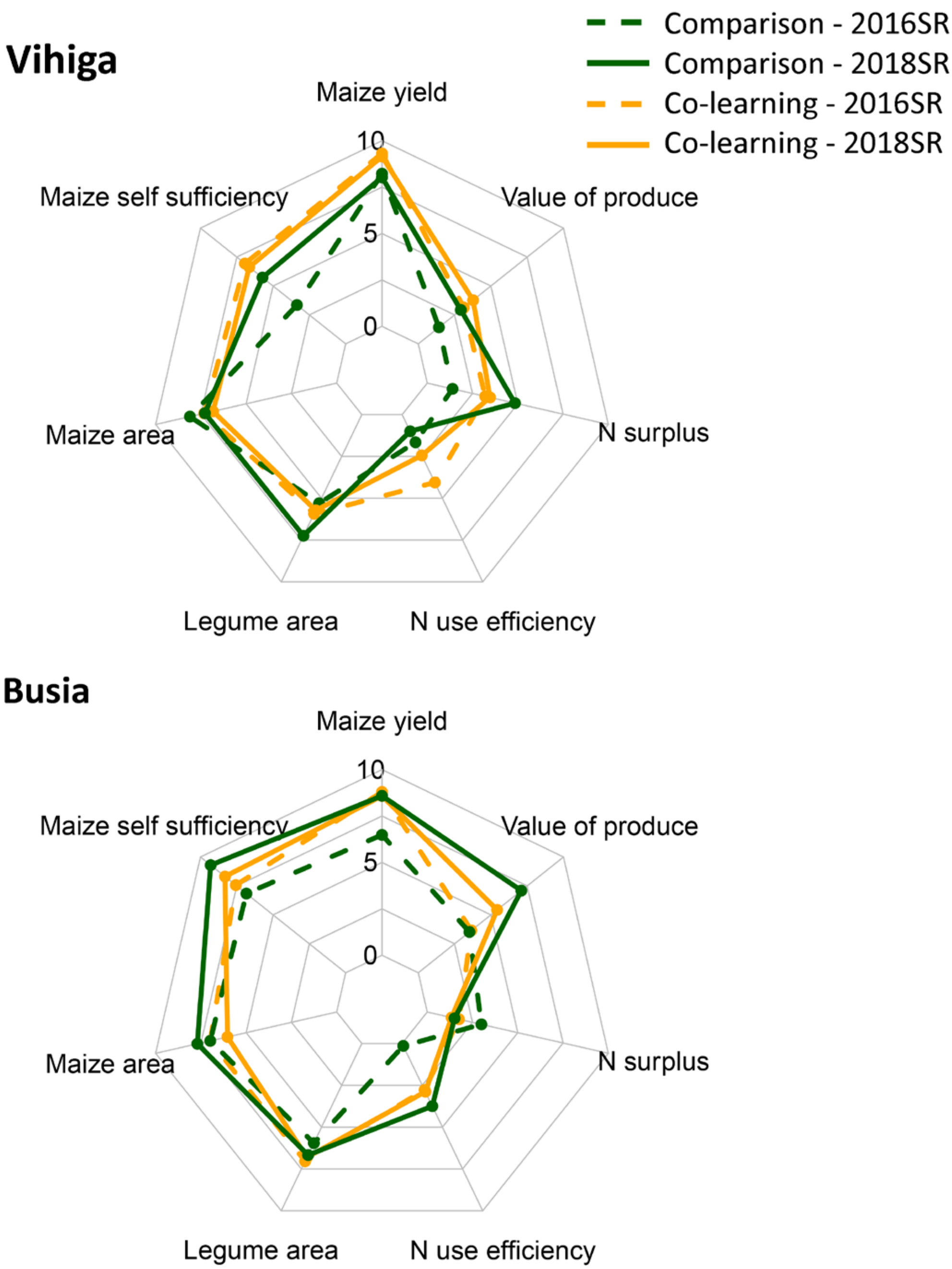

Fig. 4.7: Spiderweb diagrams with average indicator scores per indicator for comparison and co-learning farmers in Vihiga and Busia. Dashed lines represent the first co-learning season, 2016SR, while solid lines represent the last co-learning season, 2018SR.

4.4 Discussion

In this study we used a diverse set of indicators to analyse five seasons of detailed farm level data, which was gathered as part of a co-learning programme in western Kenya. The integrated co-learning approach (Marinus et al., 2021) included an input voucher and was compared with a voucher-only approach. We assessed whether the integrated co-learning approach and/or the input voucher-only would lead to pathways of intensification or extensification and pathways of diversification or specialization. We observed a larger increase in legume area for the co-learning farmers (diversification) than comparison farmers, which led to a more diversified cropping system for the former. Both groups increased maize yields (intensification), although an increase in farm and maize areas in combination with relatively low N application rates (risk of soil N mining) also pointed to extensification. Value of produce remained below a living income for most households due to the small farm areas. Our results highlight the difficulty of enabling an increase in yields and agricultural production, while also fulfilling other environmental and economic principles that are important for sustainable intensification of smallholder agriculture.

4.4.1 Farmers' response to the voucher and integrated co-learning

The voucher resulted in an important change in input use, yields, maize area, and farm area, independent of the co-learning. Increased maize yields and subsequent increased farm level production resulted in fulfilling maize self-sufficiency for most households. This is an important outcome of providing a USD 100 input voucher, as most households in western Kenya are maize self-sufficient for only half of the year (Valbuena et al., 2015). We found that, although the voucher was important in alleviating capital constraints for agriculture at household level, co-learning was key to facilitate more complex changes such as diversification into legumes. Although taking time, the iterative learning process facilitated learning on new intercropping arrangements of maize and legumes and identified specific objectives for soybean (e.g. reducing striga incidence) and groundnut (e.g. high value of produce ha^{-1}) (Marinus et al., 2021). Co-learning can thus be used to contextualize knowledge for the breath of options that is needed for sustainable intensification (Descheemaeker et al., 2019), as illustrated by the larger improvement in several indicator scores in the co-learning groups (Fig. 4.7). Our analysis also showed that there was a wide variety of indicator scores among households.

Specialization in maize was done by households both with a small and large farm size. Large farms however, reduced their maize area again in the last season (2018SR), while small farms maintained their increased maize area. Similar increases in maize area after the introduction of an input voucher or subsidy have been described before for western Kenya (Sanchez et al., 2007) and Malawi (Chibwana et al., 2012; Holden and Lunduka, 2010), based on farmer reported maize areas. In these studies however, and increase in maize area often resulted in a decrease in legume area (Chibwana et al., 2012; Holden and Lunduka, 2010). For small farms, maintaining the large maize area was associated with farmers' objective to be maize self-sufficient (Marinus et al., 2021).

The increased diversification into groundnut and soybean by farmers with small and medium farm areas was in line with the findings of Franke et al. (2014), who simulated benefits of diversification with legumes for different farm types in Malawi. Diversification is important for spreading risks (crop failure, low prices), and for nutritional and rotational benefits (Vanlauwe et al., 2019). On the smallest farms, legumes were mainly intercropped with maize resulting in limited benefits due to land constraints. However, on larger farms, labour constraints were limiting the expansion of legumes, similar to the findings of Franke et al. (2014). This would imply that developing and promoting legume-specific, small-scale mechanization, such as groundnut diggers for harvesting and shellers (Tsusaka et al., 2017), may be required to enable diversification for households with a large farm area.

4.4.2 Efference of concurrent pathways of intensification and extensification

The maize yields obtained during the programme point at the pathway of intensification as yields were two to three times greater than the yield obtained by participating farmers before the programme, and close to the benchmark of 50% of the water-limited yield. However, as the corresponding N application rates were both above and below the desirable range, sustainable intensification in terms of enhancing N use efficiency is challenging (Zhang et al., 2015).

Intensified mineral fertiliser use resulted in extremely high N application rates in Vihiga (>200 kg N ha^{-1} in the first season,~120 kg N ha^{-1} in later seasons) due to the small farm areas there, resulting in N use efficiencies below 50%. These farms of less than 0.2 ha were not able to allocate all inputs from the voucher in a useful manner, even with an increased maize area in later seasons. Maize yields were not, or in some seasons even positively, related to farm area, which goes against the inverse farm size-productivity relationship (Larson et al., 2014) but is in line with Desiere and Jolliffe (2018) and Gourlay et al. (2017). Notwithstanding higher N application rates, smaller farms did not produce better yields, which may be explained by reliance on off-farm work requiring farmers' attention and the presence of poorer soils (Franke et al., 2019), requiring longer term investments in soil fertility (Vanlauwe et al., 2010).

Extensification was observed on larger farms, who increased their farm and/or maize areas and hence distributed N over larger areas. This was most notable in Busia, as also discussed in Chapter 3, where population pressure is lower and fallow land is available. Farm area expansion was a direct result of the voucher Chapter 3. The preference of those farmers for extensification over intensification goes against one of the key objectives of sustainable intensification, namely to increase agricultural production on existing farmland (Cassman et al., 2003; Struik and Kuyper, 2017). The preference for land expansion however, seems to be a trend across SSA for crop area in general (Baudron et al., 2012; Giller et al., 2021; Jayne and Sanchez, 2021; Ollenburger et al., 2016). Increasing area may be less expensive than increasing input rates and investing in higher input rates may come with larger risks of financial losses (Burke et al., 2019; Jindo et al., 2020; Tittonell et al., 2007). N application rates were also limited by the fixed voucher size of USD 100, resulting in lower application rates for households with large maize areas. Households who bought additional fertilisers still applied N at a maximum of 50 kg N ha^{-1}, despite the advice in the co-learning workshops to apply more. This may be partly due to the active presence of One Acre Fund in the area who, as a credit provider, advises farmers to use this conservative rate of 50 kg N ha^{-1}. The relatively good yields and low fertiliser application rates may not be sustainable as they result in soil N mining. Soil N mining is common in SSA, but usually at lower yield levels and due to lower input levels than in our study (Sheahan and Barrett, 2017). We diagnosed soil N mining over multiple seasons, which may have been enabled by the application of P through the mineral fertilisers. In the P-fixing soils of the study area, P limits mineralization and strong yield responses to P can be found (Kihara and Njoroge, 2013). However, when good yields and thereby soil N mining are continued, N and other nutrients (e.g. K) may become limiting (Njoroge, 2019) and fertilizer rates needs to be adjusted.

4.4.3 Multi-criteria assessment helps to identify crucial constraints and trade-offs

We combined indicators that are important from a farmer's perspective (e.g. maize self-sufficiency, value of produce) with indicators that are important for local or national food self-sufficiency (e.g. yield) and the environment (e.g. N use efficiency, N surplus) in an integrated assessment. This analysis, in combination with the discussions with the co-learning farmers, enabled the identification of constraints and trade-offs at farm level. Achieving and even surpassing maize self-sufficiency was a first priority for farmers, because of the good maize market and the importance of having surplus food as a buffer for later seasons (Marinus et al., 2021). While explaining the limited observed diversification, this goes against a common assumption in modelling studies that farmers are likely to diversify into other crops once they are maize self-sufficient (e.g. Hengsdijk et al., 2014; Leonardo et al., 2018). Increasing the value of produce obtained from farming was a next objective for farmers. However, despite the good yields, farm area was an overriding constraint for reaching the income benchmarks. At best one-third of the households obtained a living income and half of the households reached the poverty line in Busia. In Vihiga only one out of twenty-two households obtained a living income in two seasons, while at best one-fourth reached the poverty line. Increasing farm area per household may thus be needed to increase income from farming to a living income. New employment opportunities however, will then be needed for those going out of farming (Giller, 2020), if no additional land is available or if an increase of agricultural land is not desired (e.g. Godfray et al., 2010; The Montpellier Panel, 2013).

The multi-criteria analyses was key in describing trade-offs and understanding limiting constraints in relation to sustainable intensification. For instance, we showed that a fixed voucher size per household, although fair, may not be a good incentive to promote sustainable intensification as it does not link to the key principle of increasing yields per unit land area with efficient input use. However, developing an input subsidy system that specifically aims to increase input use per unit land and which therefore needs to be linked to the farm area used by a household, may be a daunting task in current smallholder farming systems. Disaggregating the analysis per household showed that farm area limited outcomes for both small and large farms in specific ways, e.g. N use efficiencies that were below or above the desired range, respectively, while outputs (yield) were around the desired range. The multi-criteria assessment also showed that specific attention to legumes or possibly other crops for diversification is needed if the objective of a government or NGO is to diversify household income from farming by reducing the current focus on maize. Assessing adoption of new crops or varieties in such programs needs multi-season studies (Glover et al., 2019) as our results showed that the legume area per farm differed per season and not necessarily according to the season when legumes are most commonly cultivated. The principles, criteria and indicator framework, following Florin et al. (2012), was useful in being explicit on the underlying assumptions, i.e. criteria, on when an indicator contributes to sustainability. Some of these assumptions, e.g. on crop area, can be subjective and thereby require transparency on why they were chosen and which benchmarks were used (Marinus et al., 2018).

4.5 Conclusions

We compared farmer responses to an integrated co-learning approach, including an input voucher, to a voucher-only approach which aimed to sustainably increase farm level production. We analysed whether farmer responses were indicative of pathways towards sustainable intensification over a period of five seasons by applying an indicator framework. The integrated co-learning approach was key in facilitating the more complex changes in farm management, such as diversification through an increase in legume area. Other responses were mainly a result of the input voucher itself.

Increased input use led to increased yields and production (intensification), making most households maize self-sufficient. Increases in maize area and farm area on already relatively large farms resulted in relatively low N application rates and too high N use efficiencies, pointing at extensification. Small farms were only just maize self-sufficient and their value of produce remained below the poverty line for most households. Obtaining a living income was only possible on larger farm areas. Our multi-criteria analyses thereby highlights the difficulty of supporting pathways towards sustainable intensification for the diversity of smallholder farmers. Improving livelihoods requires changes that go far beyond the farm level. Smallholder farmers in western Kenya and in many rural areas of sub-Saharan Africa are essentially part-time farmers who depend on many sources of income. To increase income from farming for instance, farm areas need to increase, requiring off-farm employment opportunities for those going out of farming. Whether sustainable intensification of smallholder agriculture will actually happen may therefore depend on how changes in farm structure – that is capital, land and labour – are facilitated at farm level and as part of the wider socio-economic developments within a country.

Chapter 5

What farm size sustains a living? Exploring future options to attain a living income from smallholder farming in the East African highlands

This chapter is under revision for Frontiers in Sustainable Food Systems as:
Marinus, W., Thuijsman, E.S., van Wijk, M.T., Descheemaeker, K., van de Ven, G.W.J., Vanlauwe, B., Giller, K.E., (under revision). What farm size sustains a living? Exploring future options to attain a living income from smallholder farming in the East African highlands.

Abstract

Smallholder farming in sub-Saharan Africa keeps many rural households trapped in a cycle of poor productivity and low incomes. Two options to reach a decent income include intensification of production and expansion of farm areas per household. In this study, we explore what is a 'viable farm size', i.e. the farm area that is required to attain a 'living income', which sustains a nutritious diet, housing, education and health care.

We used survey data from three contrasting sites in the East African highlands—Nyando (Kenya), Rakai (Uganda) and Lushoto (Tanzania) to explore viable farm sizes in six scenarios. Starting from the baseline cropping system, we built scenarios by incrementally including intensified and re-configured cropping systems, income from livestock and off-farm sources.

In the most conservative scenario (baseline cropping patterns and yields, minus basic input costs), viable farm areas were 3.6, 2.4 and 2.1 ha, for Nyando, Rakai and Lushoto respectively—while current median farm areas were just 0.8, 1.8 and 0.8 ha. Given the uneven distribution of current farm areas, only few of the households in the study sites (0%, 27% and 4% for Nyando, Rakai and Lushoto respectively) were able to attain a living income. Intensification of production from baseline yields to 50% of the water-limited yields strongly decreased the viable farm size, and thereby enabled 92% of the households in Rakai and 70% of the households in Lushoto to attain a living income with their current farm area. For Nyando however, intensification of crop production alone was not enough, but including income from livestock enabled the majority of households (73%) to attain a living income on their current farm areas.

Our scenarios showed that increasing farm area and/or intensifying production is required for smallholder farmers to attain a living income from farming. However, such changes require considerable capital and labour investment, and possibly land reforms. Hence, smallholders would require support (e.g. input subsidies), protection (e.g. secure land access, price protection) and alternative off-farm employment options. Integrated policy is therefore imperative for all to attain a decent living.

5.1 Introduction

It has been estimated that of the world's poor, almost two thirds work in agriculture (Olinto et al., 2013). In Sub-Saharan Africa (SSA), smallholder farming can be a vicious cycle of low productivity and limited re-investment, keeping farming households trapped in poverty (Tittonell and Giller, 2013). The massive engagement in agriculture therefore likely expresses a lack of access to alternative livelihood sources, and farming being a last resort (Koning, 2017; van Vliet et al., 2015). Farming is currently not of interest for youth, who commonly have other aspirations (e.g. Ramisch 2014; Mausch et al. 2018; LaRue et al. 2021).

Dorward et al., (2009) used their framework of 'hanging in', 'stepping up' and 'stepping out' to describe (limited) opportunities of farming households. When agriculture generates so little that farming households can only 'hang in', some push is required—through improved farming practices or off-farm sources—to enable 'stepping up' towards more lucrative farming, or 'stepping out' of farming towards other sectors such as industry, for instance (Dorward et al., 2009). The pressure to step up or out of farming increases, because cultivated areas per farm seem to be decreasing—and more so for those who already have the smallest cultivated areas (Giller et al., 2021; Headey and Jayne, 2014; Jayne et al., 2014).

With ever smaller farms, it becomes increasingly urgent to intensify production or to pursue alternative livelihood strategies. Simultaneously there is a growing demand for food from the burgeoning population in SSA, requiring intensification of farming in order to be self-sufficient at national level (van Ittersum et al., 2016). However, even under intensified production, farms can simply be too small to obtain a decent living (Giller et al., 2021; Harris and Orr, 2014). This requires to study the combination of imperative questions of how can smallholder incomes be increased, given their small farm sizes, while also a national level, agricultural production for food self-sufficiency needs to increase (Giller, 2020). In pursuit of the Sustainable Development Goals (SDGs; United Nations - Economic and Social Council, 2016)—and SDG 1 Zero Poverty and SDG 2 No Hunger, in particular—it is important to understand whether and how farming can be(come) a viable livelihood strategy, especially for the smallest farms. Whether through subsidies to increase yields, through land reform to increase farm sizes or other measures (Koning, 2017), the protection and support of the smallest farms needs to be considered to *leave no one behind* in the SDGs.

Many studies have shown that current, small farm sizes limit the incomes of smallholder farmers (e.g. Frelat et al., 2016; Chapter 3). Others have also calculated what farm area would be required to reach the poverty line in dryland farming systems in SSA and India (Gassner et al., 2019; Harris and Orr, 2014). So far however, no studies have determined the minimum farm area to reach the living income benchmark. Moreover, earlier assessments mainly considered current cropping practices without exploring the effects of using more profitable crops (e.g. vegetables). In this study we use 'living income' as a benchmark for the viability of farming (Anker and Anker, 2017a; van de Ven et al., 2020). The living income concept has recently gained attention as a new benchmark (Living Income Community of Practice, 2021).

It estimates the income that is required for a decent living (Anker, 2011; van de Ven et al., 2020), on the basis of the principles in the universal declaration of human rights (United Nations General Assembly, 1948). It therefore includes a nutritious diet, housing, education and health care (Anker, 2011; van de Ven et al., 2020). The commonly used poverty line benchmark considers the minimum cost of living in the poorest countries in the world (Chen and Ravallion, 2010; Ravallion et al., 1991). As such, the living income is an addition to the commonly used poverty line benchmark (van de Ven et al., 2020). Van de Ven et al. (2020) recently applied the living income concept to rural households in smallholder farming systems.

The overall goal of this paper is therefore to explore what farm area would be required to attain a living income from farming, and we refer to this as the 'viable farm size'. We first assessed how current smallholder incomes (reported in survey data) compared with the site-specific living income thresholds, and investigated the contributions from crops, livestock and off-farm income. We then estimated viable farm sizes for several scenarios: first on the basis of current yields and crop area allocation, then on the basis of possible future intensification (increased yields levels and then in addition more profitable crop configurations). Moreover we examined contributions from livestock and off-farm sources to income and how they affect the viable farm size. Lastly, we compared current farm sizes with viable farm sizes. Our analysis is focused on three sites in the East African highlands: Nyando in Kenya, Rakai in Uganda and Lushoto in Tanzania, which offer interesting contrasts in farming systems.

Our research was guided by the following research questions:

1) What percentage of the farming population currently achieves a living income?
2) What farm size can provide a living income with current cropping systems—i.e. what is a viable farm size?
3) What are the implications of (a) intensification of the cropping system and (b) considering other sources of income, on the viable farm size?

5.2 Methodology

5.2.1 Three contrasting sites

Survey data was used from three contrasting sites in East Africa: Nyando in Kenya (2016), Rakai in Uganda (2017) and Lushoto in Tanzania (2015). All three sites have bi-modal rainfall patterns that allow two cropping seasons each year. Nyando is located in the mid-lands of western Kenya, on the slopes next to Lake Victoria. Small streams and rivers cross the area from the upland areas towards the lake. As these river valleys often flood, and they are commonly used for grazing livestock, while crops are cultivated on the elevated areas. Crops and livestock are both important for household income. Common crops are maize, beans and sorghum (Kung'u and Namirembe, 2012; Mango et al., 2011). In Nyando, the relative importance of livestock is much larger than in Rakai and Lushoto. Rakai is located in the southern part of central Uganda and is characterized by an undulating landscape. It has a diverse cropping system, distinguishing itself from the other two sites by the importance of perennial crops, i.e. coffee and East African highland banana (referred to as banana hereafter). Other important crops are beans, maize and cassava (Kyazze and Kristjanson, 2011). Lushoto is located in the west Usambara mountains in northern Tanzania and has an undulating, hilly landscape. Valley bottoms are commonly used to grow vegetables such as cabbage and tomato, which are transported for sale in urban markets in Tanga and Dar es Salaam. Other important crops are maize, beans and Irish potato (Lyamchai et al., 2011).

5.2.2 Estimating current value of crops and household income

The Rural Household Multi-Indicator Survey (RHoMIS; Hammond et al., 2017) formed the primary data source. RHoMIS offers a relatively rapid and largely standardized questionnaire, aimed at estimating the wellbeing of farming households. The survey was executed in 2016 in Nyando (155 households), in 2017 in Rakai (113 households), and in 2015 in Lushoto (120 households). From this household-level dataset, we extracted variables on household composition, total area cultivated, production metrics and value received (Fig 1 a and b). Production in the previous year was reported for each type of crop grown and livestock owned, as well as the fractions consumed and sold, and the total price received for the sold amount. From these variables we derived the price per crop and livestock product per household. Prices were triangulated with prices from literature and where needed replaced by prices from literature. This was in particular the case for crops for which it is difficult to derive prices per kg, e.g. banana which is sold per bunch and when reported prices deviated a lot from literature (Supplementary materials 5.1). We then calculated the total value of crop and livestock produce per household, at the median price per site of each product. All prices of products were standardized to 2017 (year of the latest survey and converted to USD purchasing power parity (USD PPP) to enable comparison among sites. Income from off-farm sources was reported as the proportion of total income at household level, so we derived its value from the total value of sold farm produce (Hammond et al., 2017). We refer to 'value of produce'

1. Estimating current value of crops and total household income

1a. RHOMIS survey data

Variables reported in RHoMIS:
- Household size (number per age category)
- Cultivated area
- Crops grown

- Crop production (kg year^{-1} [Nyando&Lushoto]; kg season^{-1} [Rakai])
- Crop proportion sold / consumed / fed to livestock
- Value received for sold produce
- Crop area proportion (RHOMIS defines little = 0, little = 0.1, under half=0.2, half = 0.5, most = 0.7, all = 0.9)

- Livestock owned
- Value received for sold livestock (products)

- Proportion of income that is from off-farm sources

1b. Data processing

Variables derived from RHoMIS, all per household:
- Household size (adult equivalents)
- Cultivated area (ha)
- Number of people growing each crop

- Crop area proportion (re-scaled to sum to 1)
- Crop price (USD PPP kg^{-1})

>> *We set all prices at median value per crop type*

>> *Prices were triangulated with literature*
- Total value of crops (USD PPP year^{-1}, sold + consumed)

- TLU
- Total value of livestock products (USD PPP TLU^{-1} year^{-1}, sold + consumed)

>> *We set all prices at median value per livestock type*

- Total off-farm income (USD PPP year^{-1})

2. Preparing baseline data for scenario explorations

2a. Triangulation of crop values

Information that was not available in the RHOMIS survey was derived from literature:
- Crops grown: now specified separately for the short and long cropping seasons in all sites (literature)
- Maize and beans assumed to be intercropped in all sites (literature)
- Crop yields: season-specific values (literature)

2b. Simplification

>> *We set household size to the median per site*

We focus on main crops per season only, per site:
- Crops with (median area proportion * proportion of the population growing the crop) > 5%, per season
- Other crops & crop areas are excluded from the analysis
- Area proportions of main crops are re-scaled to sum to 1 (bean area is equated to that of maize, and not summed)

3. Incremental scenarios to estimate the viable farm size

B1: baseline yields
- Crops only, at baseline yields

\+

B2: baseline yields - costs
- Requirements of fertilizer for main crops was estimated based on the ‘soil supply yield’ (literature, experts)
- Costs of seed and fertilizer were subtracted from the value of crop produce (literature)

\+

I1: improved yields
- Baseline yields were replaced with 50% water-limited yields (literature)
- Input costs were updated to match higher yields

\+

I2: profitable crops
- Crop areas were re-allocated so that 20% of the cultivated area is used for the main vegetable
- Area proportions of other main crops were re-scaled to sum to 1

\+

O1: livestock income
- An additional source of income was included: the value of livestock. This value was the median number of TLU times the median value of a TLU (RHOMIS)

\+

O2: off-farm income
- An additional source of income was included: off-farm work. This value was the median off-farm income (RHOMIS)

Fig. 5.1: A schematic overview of the progression of variables and values with every step in the methodology. TLU = tropical livestock unit; PPP: purchasing power parity (2017).

when considering the value of crops and/or livestock produced on the farm and refer to 'income' when all sources of household income are considered: i.e. value of crop produce, value of livestock produce and off-farm income. Income per household was expressed per Adult Equivalent (AE) following (OECD, 2011), using the household composition from the survey.

Living income estimates were used from Anker and Anker (2017a) for Kenya and from Van de Ven et al. (2020) for Tanzania and Uganda. Living income estimates were all standardized to 2017 (van de Ven et al., 2020). The extreme poverty line benchmark of USD PPP 1.90 was assumed to be per adult equivalent and was corrected for inflation up till 2017, so that the extreme poverty line benchmark was set at USD PPP 2.08 per adult equivalent per day in all three study sites.

5.2.3 Preparing baseline data for scenario exploration

For the exploration of viable farm sizes in current and intensified cropping systems, we first established what was a representative, baseline cropping system per site. The RHOMIS data provided information on production per farm and per year, and was not designed to capture crop yields or intercropping, and information on seasonal crop area allocation was only available for Rakai. In each of the study sites, intercropping is a common practice, and the bimodal rainfall pattern enabled that some crops are cultivated in one or in both cropping seasons. Because of this, crop yields could not be derived adequately from the survey, and resulted in unrealistically low estimates (Supplementary materials 5.2). Therefore, baseline yields were derived from literature instead of the survey (Supplementary materials 5.2). Seasonal crop cultivation patterns (which crop is cultivated in which season) were also based on literature for Nyando and Lushoto (MoALF, 2016; Chapter 4), while season-specific data was available for this from the survey in Rakai. For each of the sites, we assumed that maize was intercropped with common bean, whenever maize was cultivated. The survey-reported crop area proportions did not always add up to one (Supplementary materials 5.3), and were therefore rescaled proportionally to add up to one for each farm, for the main cropping season in each site. It was then assumed that if a crop was grown also in the minor season (based on literature), it was allocated the same area. We determined what were the main crops per site, by weighting the median proportion of farm area allocated to a crop by the proportion of the population growing it. In our simulated baseline cropping systems, we included only the main crops per site: i.e. those with a weighted area proportion equal to or larger than 5%. The weighted area proportions were then proportionally scaled to add up to one.

5.2.4 Scenarios exploring the viable farm sizes

Viable farm sizes were assessed for six incremental scenarios (Fig. 5.1). The baseline-scenarios (*B1: baseline yields* and *B2: baseline yield*- costs) were used to explore the viable farm size within the baseline cropping system. The crop intensification-scenarios (*I1: improved yields* and I*2: profitable crops*) were used to explore how possible future options for intensification—increasing yields and cultivating more profitable crops—would change the viable farm size. The other income sources-scenarios (*O1: livestock income* and *O2: off-farm income*) assessed the impact of incorporating current income from sources other than crops, namely livestock and off-farm income sources.

Baseline crop yields, crop prices and crop configuration were used to calculate the value of crop produce per ha, which was then used to calculate the viable farm size in the most basic scenario *B1: baseline yield*. This scenario only included value of produce of crops and no income from livestock or other sources. Scenario *B1: baseline yield* does not include any input costs (which were not incorporated in RHoMIS) and therefore underestimates the viable farm size. This issue was addressed in scenario *B2: baseline yield - costs*, where input costs were subtracted from the value of produce. Input cost were calculated for mineral fertilizer and for the seed of annual crops. These inputs are commonly bought in the area, although rates and use strongly differ among households (e.g. Tittonell et all. 2005). Information on input use, rates or costs per crop per household was not available from the survey. Fertilizer requirements per crop were calculated based on the baseline yield and the 'soil supply yield': the yield obtained when no fertilizers are applied, which was derived from literature. For each crop, we assumed this soil supply yield to be the same as the lowest yield commonly obtained by farmers per site, while the baseline yield was the average yield commonly obtained by farmers per site. The difference between the soil supply yield and the baseline yield (soil supply yield – baseline yield) was then used to calculate fertilizer requirements based on nutrients concentrations in harvested product, the dry matter content and nutrient use efficiencies from literature. Only relevant macro-nutrients for fertilization were considered, e.g. N and P for maize and N and K for banana (East African highland banana in Uganda). Prices were based on the commonly used mineral fertilizers per crop and site. Costs for seed were based on commonly used varieties per site and advised sowing rates.

The crop intensification scenarios *I1: improved yields* and *I2: profitable crops* considered two options for intensification: increasing yields and cultivating more profitable crops. Scenario *I1: improved yields* uses the crop configuration of the baseline scenarios, while crop yields were increased to 50% of the water-limited yield. The costs of inputs were updated relative to scenario *B2: baseline yield - costs*, proportionally to the increase in yield. 50% of the water-limited yield is considered as a possible goal for intensified crop production in SSA by 2050, which is needed to feed the burgeoning population (van Ittersum et al., 2016). Scenario *I2: more profitable crops* adds a crop area re-configuration, so that 20% of the cultivated area is allocated to the most common vegetable per site. Areas of other crops in the baseline crop configuration were scaled back proportionally.

Scenarios *B1*, *B2*, *I1* and *I2* focused on the contribution of only crops to household income. In the study sites however, livestock and off-farm income are also important contributors to incomes. When other sources of income are available besides crop production, the contribution from crops to attain a living income can be smaller and hence a smaller farm area can be viable. Livestock requires land as well, but no information was available in the survey data about the private and/or common land used for livestock keeping and almost no fodder production was reported. We could therefore only include the value of livestock produce (reported in the RHoMIS survey) in our scenarios, and not its relation to farm area required. In scenario *O1: livestock income*, the current median number of tropical livestock units (TLUs) owned per household per site was multiplied by the median value per TLU per site as reported in the survey, to estimate the value of produce of livestock and its effect on the viable farm size. In scenario *O2: off-farm income* current median off-farm income as reported in the survey was included and its effect of the viable farm size assessed.

5.2.5 Understanding differences in scenario outcomes among sites

Site-specific values for each of the variables were used in calculating the viable farm size. To reveal which variables most strongly determined differences among sites in the scenario outcomes, we ran the model for calculating the viable farm size five times, once for each additional variable used in the calculations for scenario *B1: baseline yield*. In the first run, variable values (crops and crop allocation, yields, prices, living income threshold, household size) in all sites were set at the same value: the value for Rakai. In the next step, crops cultivated and their area allocation were made site-specific, so that the site-specific yields (for site-specific crops) could be investigated in next step. In every next step, one more variable was made site-specific, starting with variables that were more related to the cropping system: first yields, then prices, then the living income threshold, then household sizes. Relative differences among steps and among sites were compared to assess which variables most strongly explained differences in outcomes among the three sites. The order of the steps did not influence the analysis as we only compared the relative differences between steps and sites.

5.3 Results

5.3.1 Current income

Current income from all sources

When considering all sources of current household income, only 29% of the households in Nyando, 27% in Rakai and 17% in Lushoto obtained a living income (Fig. 5.2A). The poverty line was reached by 61% of the households in Nyando, and just 50% in Rakai and 35% in Lushoto. At the left tail of the income distribution, crop produce for own consumption made the largest contribution to incomes in all three sites (Fig. 5.2B). More than three quarters of the households had some off-farm income in Nyando and Rakai, while almost all households in Lushoto relied on farming only. In Nyando and Rakai, the contribution of off-farm income to the total household income was larger among households with a medium and high income than among households with a low income. Median off-farm income, for those receiving it, was also highest in Nyando (0.64 USD PPP AE^{-1} day^{-1}), followed by Rakai (0.32 USD PPP AE^{-1}

day^{-1}) and Lushoto (0.23 USD PPP AE^{-1} day^{-1}), and see also Supplementary materials 5.4. There was no information available from the survey about whether off-farm income sources were used to invest in farm activities. The contribution of livestock to value of farm produce was much larger in Nyando and Lushoto than in Rakai. In Nyando, the contribution of livestock was often larger than that of crops. This may largely be due to the relatively large numbers of livestock—mainly cattle—kept in Nyando (Supplementary materials 5.5), at a median of 8.8 TLU per household compared to 1.6 and 1.4 TLU per household in Rakai and Lushoto (Table 5.1). The value of produce obtained per TLU was largest in Lushoto, however, where marketing dairy products is common, resulting in relatively high value of produce per TLU owned. In Rakai many households were holding pigs (Supplementary materials 5.5). Survey data revealed no relation between cultivated area and the number of TLU owned (Supplementary materials 5.6)

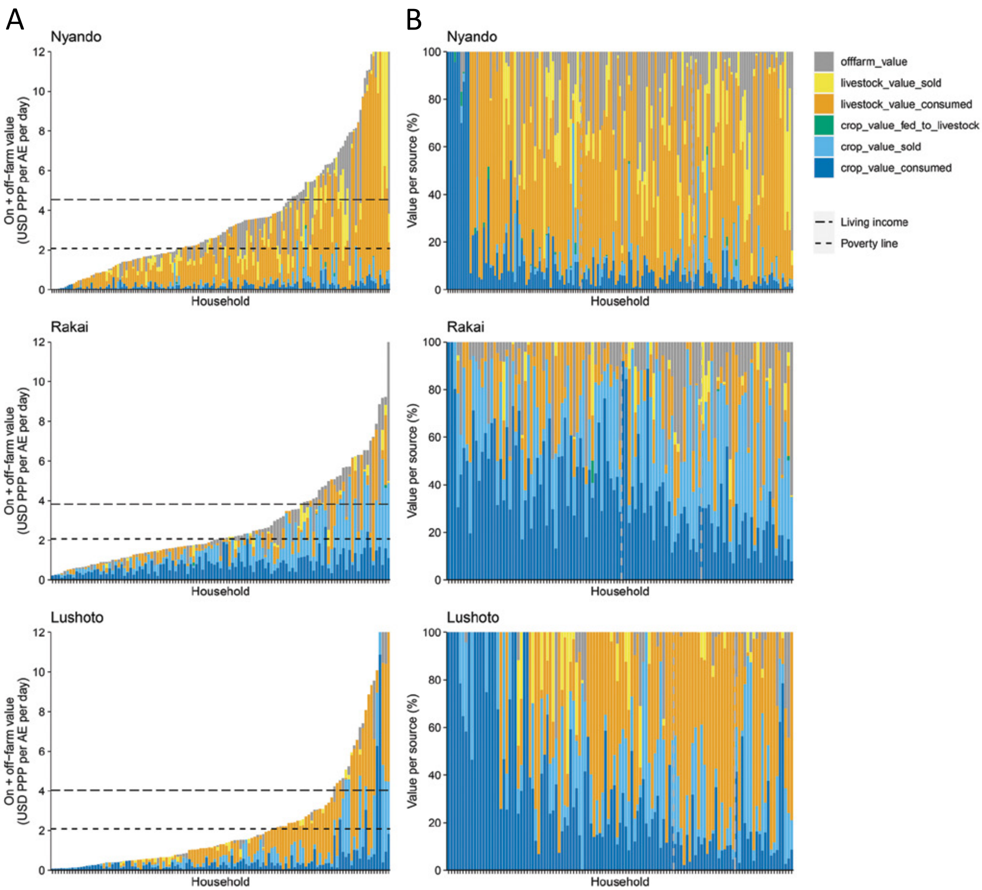

Fig. 5.2: Current household income in relation to the poverty line and living income benchmarks (A) and the relative contribution of different income sources to the current income (B). Households in panel B are ordered the same as in panel A.

Value of crop produce

None of the households in Nyando obtained a living income from the total value of crops alone (Fig. 5.3A). In Rakai 20% of the households and in Lushoto about 10% of the households obtained a living income from value of crops alone. Income from crops was generally highest in Rakai, where high-value perennial cash crops were more common. The most important crops in terms of value produced differed per site (Fig. 5.3B). Maize was most important in Nyando and Lushoto, constituting 49% and 42% on average of the total value of crops, respectively. In Rakai coffee (29%) and banana (23%) were the most important crops in terms of value of produce. Some other specific crops, that were important per site are sorghum (13%) and sugarcane (7%) in Nyando, Irish potato in Rakai (11%) and Lushoto (10%). Beans were common in all three sites and most important in terms of value of produce in Lushoto (23%). Among households that obtained a low total value of crops, specific crops were relatively more prevalent: sorghum in Nyando and beans in Lushoto.

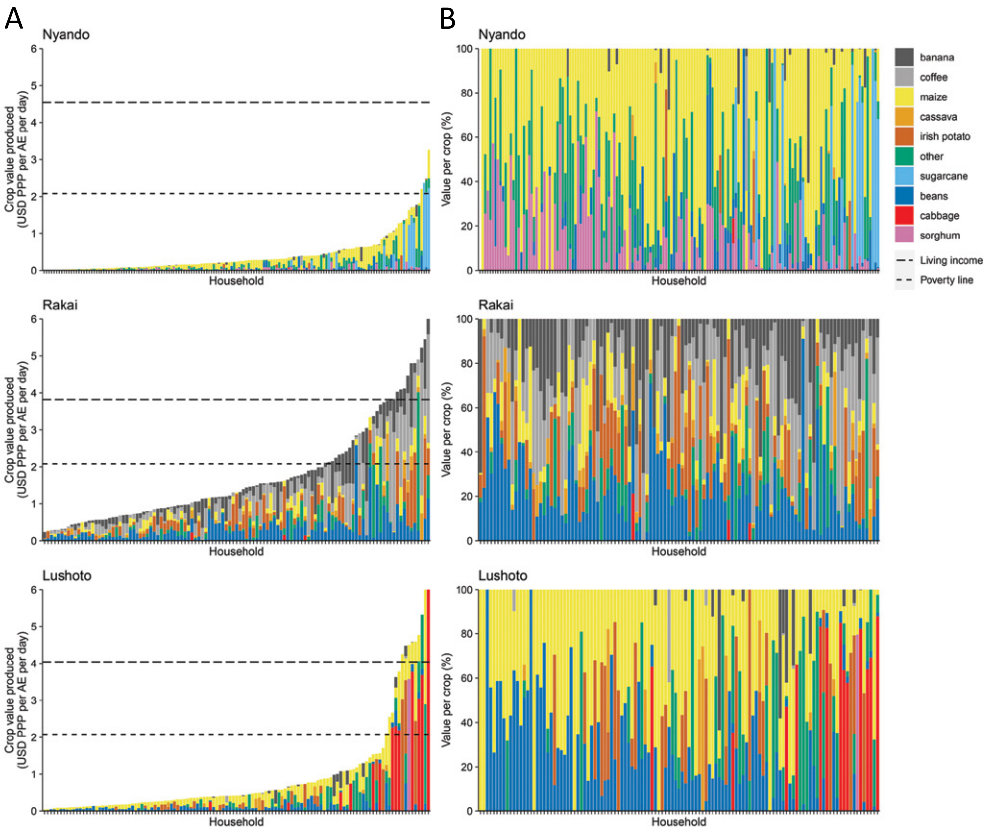

Fig. 5.3: The current value of crop produce in relation to the poverty line and living income benchmarks (A) and the relative contribution of different crops to the total value of crops (B). The value of crop produce is the sum of the value sold, consumed and fed to livestock. Households in panel B are ordered the same as in panel A.

Table 5.1: Current livestock ownership and value of produce per TLU (tropical livestock unit).

Site	% of households owning livestock	TLUs owned[1]	Livestock value of produce per TLU (USD PPP TLU^{-1} $year^{-1}$)	Livestock value of produce per AE[2] (USD PPP AE^{-1} day^{-1})
Nyando	100	8.8	322.03	1.48
Rakai	93	1.6	369.52	0.28
Lushoto	100	1.4	1034.63	0.90

[1] Median, calculated from the households owning livestock;

[2] AE: adult equivalents

Farm areas and the total value of crop produce were very unequally distributed (distributions shown in Supplementary material 5.4). In Nyando and Rakai, those who obtained a larger value of crops (>85 percentile) tended to have larger farms than those who produced less crop value (Fig. 5.4).

5.3.2 Viable farm size

Scenario *B1: baseline yield* resulted in viable farm sizes of 2.5 ha, 2.0 ha and 1.6 ha for Nyando, Rakai and Lushoto respectively (Fig. 5.5 and Supplementary materials 5.7). This was a threefold difference with the current median cultivated area in Nyando (0.8 ha) and a twofold difference for Lushoto (0.8 ha), while for Rakai the viable farm size was similar to the current median cultivated area in Rakai (1.8 ha). The relatively small viable farm size estimate for Lushoto can be explained primarily by the combination of relatively high-value crops (see effect of crops and crop allocation, Step 1, Table 5.2), and the smallest median household size of all sites (Step 6), which both result in a smaller viable farm size. In Nyando, crop prices were relatively low (Step 4), while the living income was relatively high (Step 5), resulting in a relatively large viable farm size. Crop prices were most favourable in Rakai (Step 4), e.g. beans were most expensive in Rakai, although less than double compared to the other two sites. Yield differences had the smallest effect on the outcome differences among the three sites (Step 3).

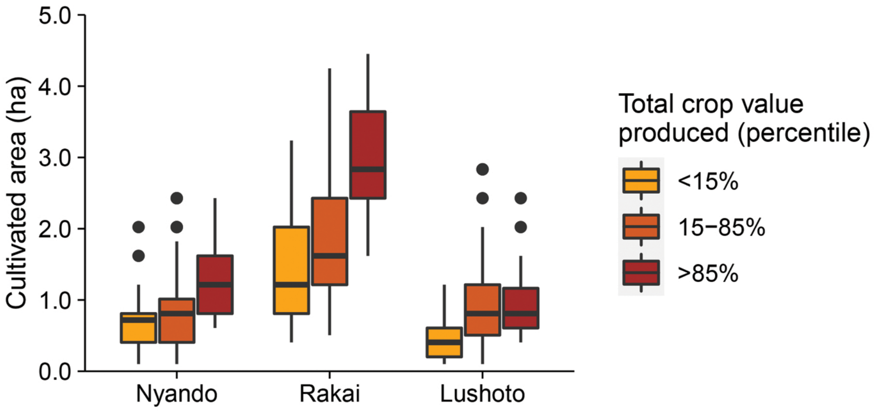

Fig. 5.4: Cultivated areas for households in relation to a low (<15 percentile), medium (15-85 percentile) or high (>85 percentile) current total value of crop produce.

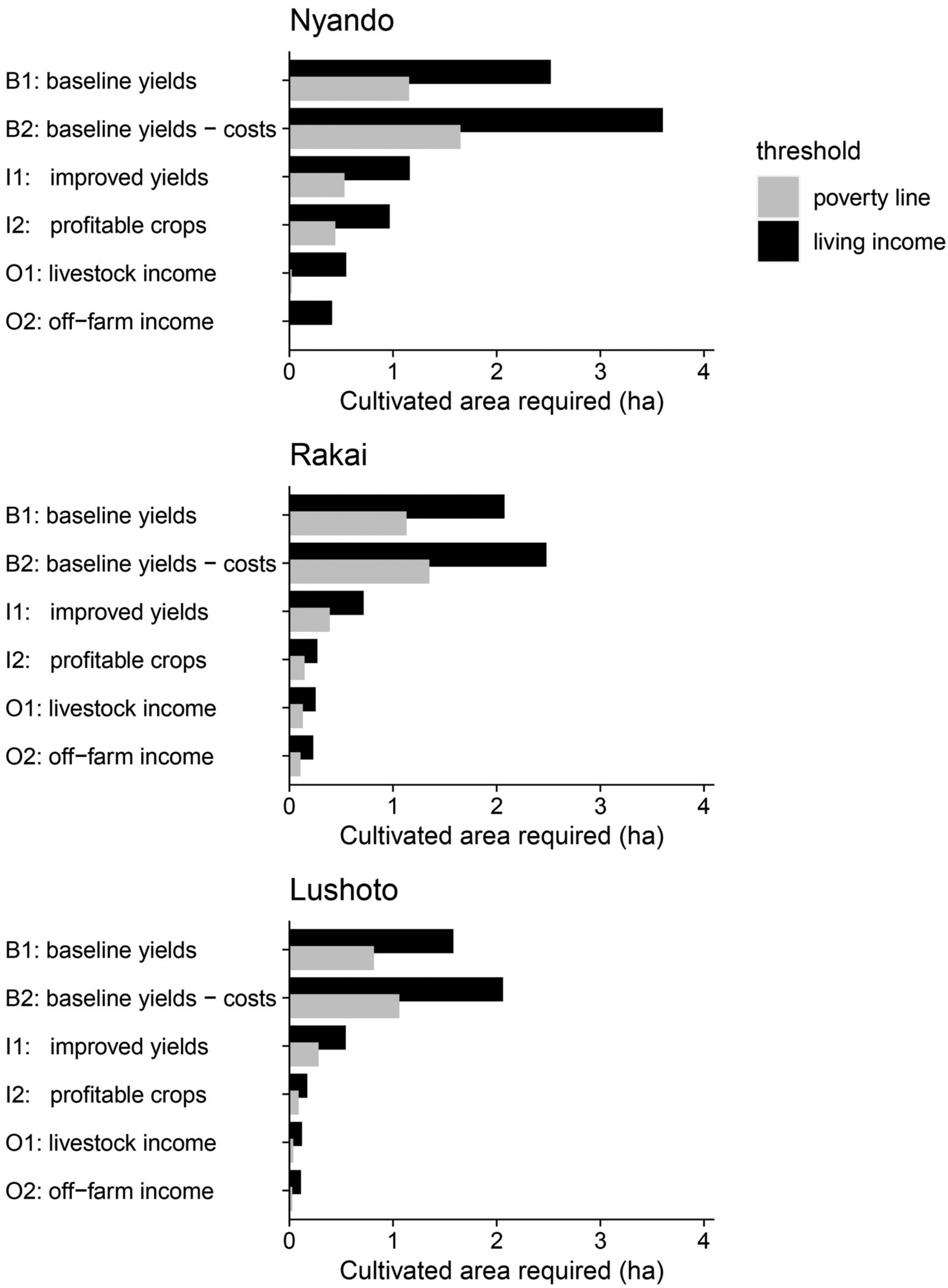

Fig. 5.5: The cultivated area required to reach the poverty line or obtain a living income (viable farm size) for a household of median size for six scenarios. All scenarios are incremental, meaning that each scenario builds on all improvements and assumptions of the previous scenario.

Table 5.2: Viable farm sizes without or with the site-specific values per variable that were included in the estimating the viable farm size, using scenario *B1: baseline yields*. In step 1, values were set at the values for Rakai, for each variable. In each subsequent step, one more variable was set at its site-specific values. Asterisks indicate the variables for which site-specific values were included.

Site	Viable farm sizes (ha)					
	Step 1: crops & allocation yields prices living income household size	Step 2: *crops & allocation yields prices living income household size	Step 3: *crops & allocation *yields prices living income household size	Step 4: *crops & allocation *yields *prices living income household size	Step 5: *crops & allocation *yields *prices *living income household size	Step 6: *crops & allocation *yields *prices *living income *household size (full *B1* scenario)
Nyando	2.0	1.9	1.9	2.4	2.8	2.5
Rakai	2.0	2.0	2.0	2.0	2.0	2.0
Lushoto	2.0	1.5	1.6	2.0	2.1	1.6

The crop intensification scenarios strongly reduced the viable farm sizes. Increasing yields to 50% of the water-limited yield (scenario *I1: improved yields*) had the largest effect and result-ed in viable farm size estimates that were three times smaller than in scenario *B2: baseline* *yields - costs* (Fig. 5.5). Allocating 20% of the cultivated area to the most common vegetable per site (scenario *I2: profitable crops*) resulted in a larger area reduction in Rakai and Lushoto than in Nyando due to the higher gross margin of tomato and cabbage in Rakai and Lushoto respectively as compared to kale in Nyando. Vegetables however, currently only occupied a minor part of the cultivated area and only few households had >20% of their cultivated area under vegetables: 6%, 15% and 9% of households in Nyando, Rakai and Lushoto.

Including livestock as an additional income source (scenario *O1: livestock income*) had only a limited reducing effect on the viable farm sizes, in comparison to the crop intensification scenarios (Fig. 5.5). The largest effect was found in Nyando, where the number of cattle owned was relatively large (Table 5.1). This cattle was likely sustained from grazing on common land around nearby streams and wetlands. Households in Rakai and Lushoto owned much fewer TLUs on average and therefore had less income from livestock (despite the relatively high value per TLU in Lushoto, due to dairy marketing). The estimates of the viable farm size therefore decreased only very little. Including off-farm income as a contributor to a living income (scenario *O2: off-farm income*), again resulted in a relatively large decrease in the viable farm size in Nyando (Fig. 5.5). The sum of income from livestock and off-farm sources was USD PPP 2.12, which is more than the poverty line, indicating the importance of alternative income sources in Nyando. Income from crops would not be required to reach the poverty line, with median incomes from livestock and off-farm sources in Nyando, but the living income was not reached with these non-crop sources only. Including off-farm income showed a small effect in Rakai and Lushoto.

5.3.3 Comparing viable farm areas with current cultivated areas

By comparing viable farm sizes with the current cultivated areas we assessed what proportion of the current population would be able to attain a living income with their current farm area, for each of the scenarios. Because the scenarios were incremental, every next scenario resulted in a smaller estimate of the viable farm size (except scenario *B2: baseline yields - costs* which incorporated costs) and a larger number of households in the study populations had access to the estimated viable farm size. This number strongly depended on the shape of the distribution of current farm sizes (Fig. 5.6), which was skewed towards smaller farm sizes in Nyando and Lushoto. In each of the sites, a small proportion or none of the households currently cultivated an area larger than the viable farm sizes of the baseline scenarios (*B1: baseline yield*, *B2: baseline yields - costs*). In the conservative scenario *B2: baseline yields - costs* this was 0%, 27% and 4% for Nyando, Rakai and Lushoto respectively. The yield-improvement scenario (*I1: improved yields*) decreased the viable farm size so much in Rakai and Lushoto, that it covered the flattest part of the curve with a major shift in the proportion of the population having a viable farm size, 92% and 70% in Rakai and Lushoto respectively. In Nyando, apart from crop intensification, income from livestock was required (*scenario O1: livestock income*) for the majority of the study population (73%) to be able to attain a living income from their currently cultivated area.

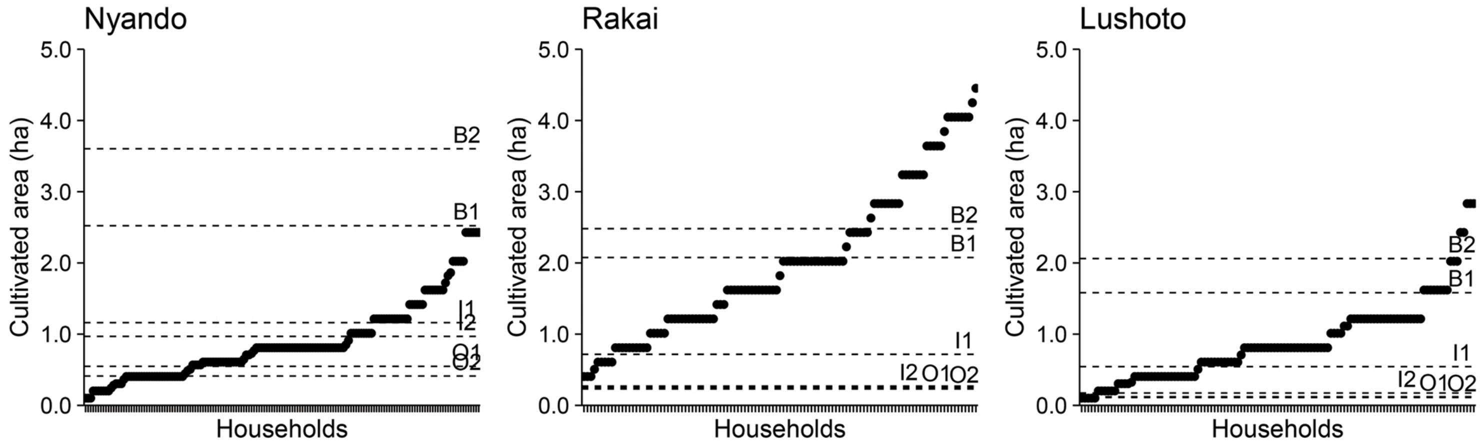

Fig. 5.6: Distributions of current cultivated areas per household as reported in the survey, and the cultivated area required to attain a living income (viable farm size; dashed horizontal lines) for six scenarios. Full scenario names: *B1: baseline yields, B2: baseline yields - costs, I1: improved yields, I2: profitable crops, O1: livestock income, O2: off-farm income*.

5.4 Discussion

In this study we first compared current smallholder farmers' incomes in three sites in the East African highlands with a new income benchmark for a decent living: the living income. We then assessed what area would be required to attain a living income from smallholder farming—the viable farm size—and compared this with current cultivated areas. We explored six incremental scenarios, which included intensification (increased yields and a change in crop configuration) and other sources of income (livestock and off-farm). For each scenario, we estimated the viable farm size. This study is the first that uses the living income as a benchmark for establishing what would be a viable farm size. It builds on earlier work in SSA with the poverty line as a benchmark (Harris and Orr, 2014), and similar historical assessments of what would be 'decent' incomes for farmers, in Europe after the second world war (Van Merriënboer, 2019). Currently such calculations are still made by the European Union to estimate subsidy requirements for farmers' incomes to be comparable with non-farm jobs in the EU (EU, 2020). Our results explored viable farm sizes but do not provide a precise answer to the question what a future farm size would need to be as they are based on several assumptions and do not consider all complexities of making a living from farming. The scenario with baseline yields and input costs (scenario *B2: baseline yields - costs*) was the most conservative, providing a first rough estimate of what a viable farm sizes would be under current production levels and market prices for an average sized family: 3.6 ha, 2.4 ha and 2.1 ha for Nyando, Rakai and Lushoto respectively, which is 4.5, 1.3 and 2.5 times the current, median cultivated area in the three sites. Currently, only 0%, 27% and 4% of the population had a cultivated area that was larger than the viable farm size in scenarios *B2: baseline yields - costs*, in Nyando, Rakai and Lushoto respectively. Current cultivated areas were only large enough for most households attain a living income in the intensification scenarios for Rakai and Lushoto (Fig. 5.6). For Nyando this was only the case when other sources of income, i.e. livestock, were also included. This indicates that the cultivated area per household would have to increase and/or that cropping systems would have to intensify considerably, and for Nyando livestock would need to be included as well, for farming households to attain a living income from farming.

5.4.1 Current smallholder incomes

The analysis of current income clearly showed the limited value that is currently accrued from cultivating crops, with currently only 11% of the households obtaining a living income from crops in Rakai, while this was 8% in Lushoto and none of the households in Nyando. Smallholder farmers rely on diverse livelihood activities besides crop cultivation, although poorer households tended to rely on cropping primarily, i.e. the 5-15 % of the households with the lowest household income. With all income sources combined, only 29% of the households in Nyando, 27% in Rakai and 17% in Lushoto obtained a living income, based on the survey data. Crops contributed only to part of the total household income and this contribution strongly varied per site. Considering crops alone, at best, less than 20% of the households currently obtained a living income (Rakai), while none made a living income in Nyando. Households with low total household income often depended on farming only and used the largest part of their farm produce for home consumption. This may imply that investing in crops and obtaining a good income from crops alone is difficult in current farming systems. In order to increase yields and intensify, farmers need viable options to invest in (Vanlauwe and Dobermann, 2020). Livestock and off-farm income were most important for household income in Nyando, with all households having livestock and 63% of households having off-farm income. In all three sites, these sources of income were primarily important for households with a relatively higher income. The importance of livestock and off-farm income as an income source for better-off households in the study sites is in line with earlier studies (Frelat et al., 2016; Waha et al., 2018; Wichern et al., 2017). Among the households that obtained a low total value of crops, staple crops were common (beans in Lushoto, sorghum in Nyando), rather than high-value cash crops (sugarcane in Nyando). It is unclear from the data whether the production of low-input, low-value crops is the result of preference or necessity. Limited opportunity to invest or access markets could be major constraints for possible improvements like sustainable intensification, for these households. The sparse contributions of off-farm sources to incomes in Rakai and Lushoto point at the limited current off-farm opportunities in rural areas in SSA (Headey and Jayne, 2014). Towards the left tail of the income distribution graphs, reported incomes were very low and often well below the poverty line and the living income. This suggests that the survey data under-reported current household incomes. Under-reporting of incomes is a common problem in this type of surveys (Fraval et al., 2019) that may be partly explained by food sharing among households during the lean season when food stocks start to run out (Djurfeldt and Wambugu, 2011), something that was not captured in the survey. Livestock holding seemed not related to farm area, and fodder production was only reported a few times in the survey. Assessing land use by livestock however, was not an important objective of the RHoMIS survey and may therefore not have come out clearly. Additional, more specific, data on land use by livestock could be used to assess the potential role of livestock in providing a living income, in relation to crops and cultivated area.

5.4.2 Viable farm sizes to attain a living income

Our analysis showed that current farm area are in most cases too small to attain a living income from farming, if no changes in cropping systems are made. For instance, only 0%, 27% and 4% of the households had a current farm area that was the same or larger than the viable farm size in the scenario *B2: baseline yields - costs* in Nyando, Rakai and Lushoto respectively (Fig. 5.6). This means that for farms to be viable, the area under cultivation needs to be increased and/or production intensified. There is a large gap between yields of major crops in the baseline scenarios and the improved yields in the intensification scenarios (50% of the water-limited yields), which were more than three times larger. Hence, the estimate of the viable farm size was also reduced by a factor three approximately in scenario *I1: improved yields*, compared to scenario *B2: baseline yields - costs* (Fig. 5.5). This meant that 27% 92% and 70% of the households currently had a farm area that was the same or larger than the viable farm size in Nyando, Rakai and Lushoto respectively (Fig. 5.6). Intensification to yield levels that were 50% of the water-limited yield (as in the *I1: improved yields scenario*) is possible at farm level in western Kenya, e.g. by providing a USD 100 input voucher per season (Chapter 3). Our results are therefore slightly more optimistic than those of Harris and Orr (2014), who looked at the impact of options for agronomic improvement at household level. They found that these improvements would not lead to attaining the poverty line for most households, because cultivated areas were too small. Their analysis, however, did not consider income from livestock, nor areas with high-value crops such as banana, coffee and vegetables, although they considered variable costs in more detail (e.g. labor). Among the study sites, crops were least profitable in Nyando, and it would be a challenge to attain a decent living from crops alone with current farm areas, in line with the analysis of Harris and Orr (2014). We however found that by also including livestock value of produce in Nyando, a living income could be attained with current farm sizes, i.e. 73% of the households had a current farm area that was the same or larger than the viable farm size in scenario *O1: livestock income*. By including only basic input costs (seed and mineral fertilizers) and no other costs in our study, we may have overestimated incomes from farming, and hence underestimated the farm size required to provide a living income. This and our other assumptions (e.g. using median yields and seasonal cropping patterns from literature) were made on the grounds of data availability and quality. Further research would be required to get more detailed estimates, preferably from on-farm studies, to assess the profitability of crops across farms, the yields that can be attained, and the input costs required. Our calculated viable farm sizes should therefore be seen as minimum viable farm sizes, which likely need to be larger if other costs and other limiting factors such as production risks (e.g. due to price or climate variability) would be included.

Scenarios were based on the baseline crop configurations, up till scenario *I2: profitable crops.* This choice was data-driven. We realize that once people gain investment capacity, their livelihood strategies may change, and they might move towards more capital-intensive farming strategies. Some of the crops in the baseline crop configurations are currently cultivated because they can provide at least some yield with low inputs, such as cassava for instance (Fermont et al., 2008). Once higher incomes are achieved, such crops may be replaced by more profitable crops (Chapter 4). Opportunities for cultivating high-value crops however, are limited as crops such as vegetables often have a limited demand, high input cost and highly varying prices. Moreover, suitable land for cultivating vegetables is limited, which also explains why currently only few households cultivated vegetables on more than 20% of their cultivated area. Vegetables in Lushoto for instance are only cultivated in inland valleys because of water availability, limiting the options to increase the cultivated area with vegetables (Sakané et al., 2013). Once production levels and/or the types of crops produced change, market prices will change as well, as was for instance found when maize production increased in Ethiopia (Abate et al., 2015; Spielman et al., 2010). Such fluctuations would again influence the profitability of the scenarios explored. Besides, for the case of vegetables in particular, demand may be fairly inelastic.

5.4.3 Expanding farm sizes and/or intensifying production? Implications of moving towards viable farms

A large proportion of the study populations currently did not have a viable farm size. With considerable intensification however, decent incomes appear to be within reach on the areas that are currently cultivated. To attain a decent living, farming households could therefore expand and/or intensify production, while it is likely that a combination of both options will be required (Giller et al., 2021). Both of these options would require substantial changes at the level of the farm and household, and the national and regional level, which need to be supported by policies. Moreover, such changes need to fit with households' objectives: do they want to pursue farming as a livelihood strategy or would they rather have alternative employment?

We assessed the farm area required at household level, while only considering capital through a simple assessment of input costs. More elements of farm structure – labor and capital – however, would have to be dedicated to intensification and/or expansion. Although the use of inputs such as mineral fertilizer and improved seed can be profitable in current smallholder farming systems, their use is often limited (Nin-Pratt and McBride, 2014). Increasing yields to 50% of the water-limited yield, would require considerable increases in input use: the N fertilizer requirements in scenario *I1: improved yields* for instance, were three to five times larger than at baseline yields. Such an increase in input use may require input subsidies (Jayne et al., 2018), along with other supportive policies such as price protection and improving access to markets (Koning, 2017; Wiggins, 2016), which together have shown to be able to increase yields to 50% of the water-limited yield at farm level (Sanchez et al. 2007; Chapter 3). Also Fraval et al., (2018) found that considerable improvements in farm performance can happen in a relatively short time span of three years for part of the population. Increasing the cultivated area of a farm would also require more efficient labor use. Labor constraints explain part of the current yield gap (Silva et al., 2019), and current crop choices of farmers might become more labor-constrained on larger areas (Chapter 4). Small-scale mechanization may therefore be required to improve labor productivity (Van Loon et al., 2020), in particular if farm areas would increase to attain a living income. Lastly, apart from land, labor and capital, additional knowledge will also be needed when moving towards for instance scenario *I1: improved yields*. Marinus et al. (2021) for instance describe how farmers required knowledge on specific intercropping arrangements for maize and legumes when maize growth became prolific – reaching 50% of the water-limited yield level – and thereby smothering intercropped legumes.

At the national or regional level, if farms would expand to attain a living income from farming, there may not be enough land available for all households to do so. For instance, moving from current farm areas to the viable farm areas as calculated in scenario *B2: baseline yields - costs*, would require farm areas that are 440%, 130% and 260% that of the current, median cultivated area in Nyando, Rakai and Lushoto respectively. Hence, for all farming households to be able to attain a living income, more off-farm employment opportunities would need to become available for those going out of farming (Giller, 2020; Koning, 2017). In the study sites, off-farm income sources tended to contribute much less to incomes than crop and livestock production. Sectors such as industry would therefore need to become more important in local economies. Developing local industry however, may be difficult given the poor competitiveness of SSA economies (Koning, 2017). Increasing farm areas would also require policies that result in fair allocation of land and that acknowledge the cultural importance of land. For instance, owning land can be very important for ensuring food self-sufficiency in times of need, or because the land is used as a family burial place, as is common in SSA. Land is currently unequally distributed, and the poorest and smallest farms are in an unfavourable competitive position (Chamberlin and Jayne, 2020). At a larger scale, land is also often bought as an investment by businessmen, who regularly acquire their capital in other sectors (Jayne et al., 2016; Sitko and Jayne, 2014). Competition for land and markets may further marginalize the smallest farms, while the largest grow (Headey and Jayne, 2014; Jayne et al., 2021, 2014). Land policies are thus required that support the development and protection of farming systems.

5.4.4 Concluding remarks

This study is the first to apply the living income for establishing what would be a 'viable farm size', as a benchmark for smallholder farming. We applied the approach in three sites with contrasting farming systems and used these contrasts to inform the scenarios, which considered crop intensification strategies, income from livestock and off-farm income. Our scenarios explored how households could step up and attain a decent living, while *leaving no one behind*. We found that with yields at baseline level, cultivated areas would have to increase considerably to attain a living income: more than four times in Nyando as compared to the current median cultivated area. This would incentivize the smallest farmers to step out of farming—necessitating the availability of alternative or additional employment options. Intensification scenarios however indicated that, with an increase in baseline yields to 50% of the water-limited yield more than 70% of the households would be able to attain a living income with their current cultivated area. Only in Nyando also other sources of income, such as livestock, would be needed for the majority of the population to attain a living income from farming. However, moving towards a viable farm by intensifying the cropping system and/or by increasing the farm area per household necessitates considerable changes, requiring diverse policies, e.g. stimulating input use and possibly including land reforms. Such changes may not only be needed to increase smallholder farmers income, but also to increase national food self-sufficiency for countries in SSA while populations grow. The viable farm size methodology can therefore be a useful tool in answering some of the imperative questions (cf. Giller 2020) around what is required for smallholder farming to provide a decent living.


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Chapter 6

General discussion

6.1 General findings

In this thesis I assessed pathways towards more sustainable farming systems in the East African highlands, from two perspectives. The first ,'impact-oriented' perspective was considered in Chapters 2 to 4. It started from and was embedded within current farming systems and assessed the impact of the integrated co-learning approach at farm level in western Kenya. We assessed learning outcomes, changes in farm management and the impacts at household level over a time span of five seasons, including yield increases (Fig. 6.1). Through the second, 'target-oriented' perspective we explored what changes in the farming system would be required to attain a living income through scenario analyses (Chapter 5). One of these changes was to increase yields to 50% of the water-limited yield, as a possible yield target for food self-sufficiency at national level by 2050, which was similar to the yields obtained in Chapters 2 to 4 (Fig. 6.1). In this general discussion I compare both perspectives and their outcomes to assess the opportunities and constraints for attaining such future yield and income increases. The combined perspectives thereby give an insight in possible pathways towards more sustainable farming systems in the East African highlands.

The main outcomes of the impact-oriented perspective (Chapters 2 to 4) were as follows. In Chapter 2 we developed and presented the 'integrated co-learning approach' that combined a USD 100 input voucher per season and iterative learning on sustainable intensification. Co-learning farmers had more diverse and cohesive knowledge after five seasons, than the comparison farmers, who only received the voucher. Co-learning seemed in particular key in facilitating some of the more complex changes that are required for sustainable intensification. Irrespectively of the co-learning, the voucher immediately increased farm level maize yield from less than 20% to 40-50% of the water-limited yield (Fig. 6.1). This indicates that closing yield gaps until 50% of the water-limited yield is mainly limited by capital constraints and not by technology or knowledge. A yield target of 50% of the water-limited yield is therefore within reach if capital constraints of smallholder farmers can be alleviated.

In Chapter 3 we showed that, although yields were high, value of produce from crops was still below the living income benchmark for most households due to their small farm areas. Increasing yield alone, may thus not be enough to attain a living income. Chapter 4 showed that also for other indicators, such as N use efficiency, it was difficult to reach desired outcomes and many indicator outcomes pointed towards the pathway of extensification instead of the desired intensification.

Building on the finding that farm size strongly limited farmer income (Chapter 3), in the target-oriented perspective we explored viable farm sizes for contrasting future scenarios in three sites in the East African highlands (Chapter 5). We defined 'the viable farm size' as the cultivated area required to attain a living income. Our analysis revealed that in the current baseline scenario, cultivated areas per farm would have to increase by 4.5, 1.3 and 2.5 times in Nyando (Kenya), Rakai (Uganda) and Lushoto (Tanzania) respectively, to make a living income. However, if crop yields increased to 50% of the water-limited yields, current cultivated

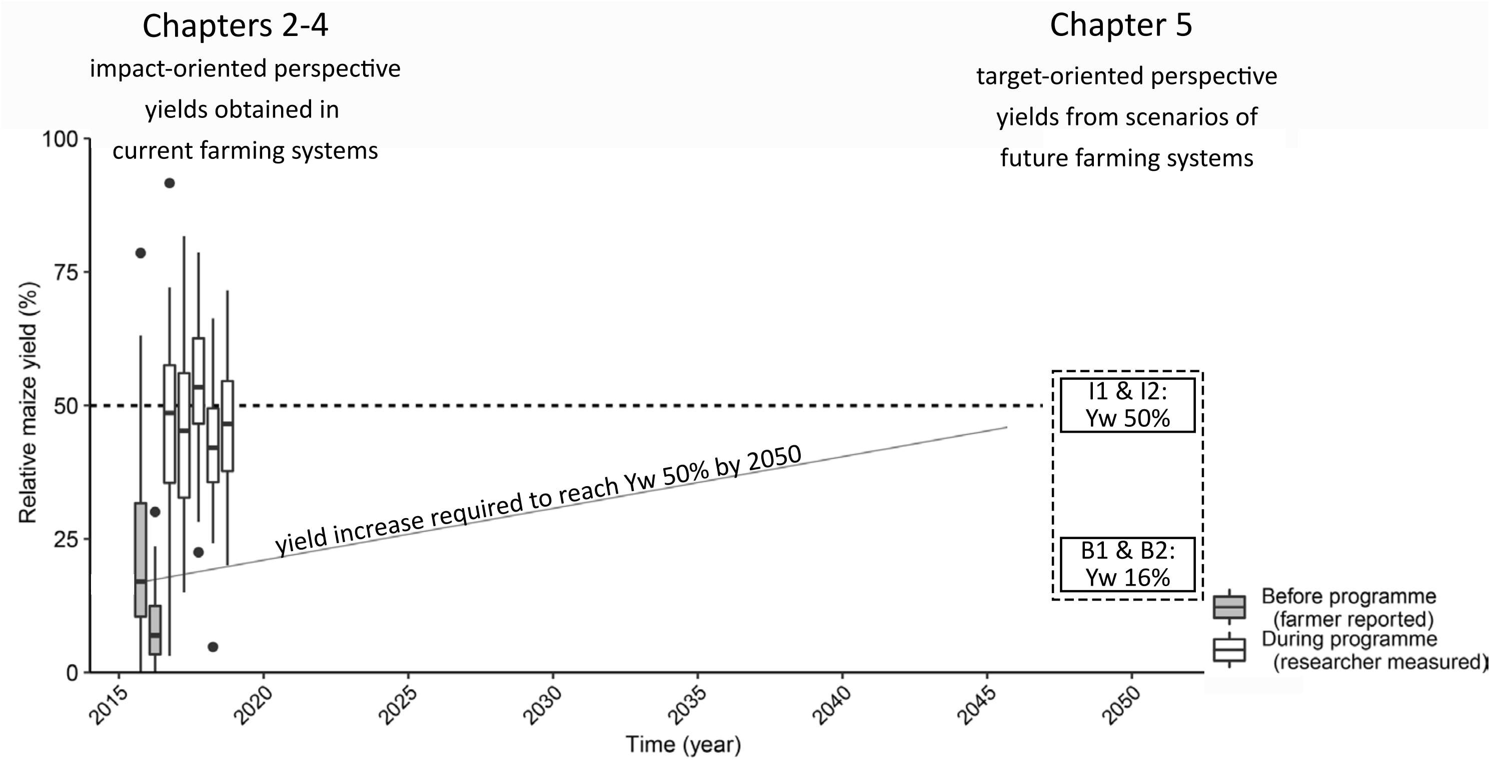

Fig. 6.1: A summary figure with yields obtained within current farming systems in Chapters 2 to 4 and future yield levels explored as part of the scenario analysis to calculate the viable farm sizes in Chapter 5. The dashed horizontal line indicates 50% of the water-limited yield (Yw 50%) as a desired yield level. Full scenario names for CH5 as shown in this figure are: *B1: baseline yield*, *B2: baseline yields - costs*, *I1: improved yields, I2: profitable crops*, see also Chapter 5 for a detailed description.

areas of most households (>70%) would be large enough to make a living income in Rakai and Lushoto. In Nyando, other sources of income, such as income from livestock, were required to make a living income.

Synthesizing the outcomes of the two perspectives reveals that increasing yields of current basic staple crops, is not enough to make a living income with current farm sizes. Larger changes are required, e.g. increasing farm area, cultivating more profitable crops such as vegetables and/or including other income sources, to make a living income from farming. Such changes may be a challenge however, both at farm or household level as well as at national level.

In the following sections I further discuss the main outcomes of this thesis. In section 6.2 I propose to prioritize specific goals of sustainable intensification. In section 6.3 I further discuss what changes are required at farm level as well as at national level to increase both yields and to make a decent living from farming. This is followed by the methodological considerations of this thesis, which amongst other topics highlights the strengths and weaknesses of using detailed farm level studies. I end the thesis with some concluding remarks.

6.2 Hit or miss: too many targets for sustainable intensification of smallholder farming?

Sustainable intensification is commonly advocated as an important development strategy for smallholder farming (Pretty et al., 2011; The Montpellier Panel, 2013; Vanlauwe et al., 2014). Our findings nonetheless, highlighted the difficulty of increasing productivity, while also meeting other economic and environmental principles (Chapter 4). From a farmers' perspective however, a large part of their primary production objectives were met with the voucher, i.e. firstly being maize self-sufficiency and secondly increasing income (Chapters 2 and 4). Certain indicators and principles may thus initially be prioritized over others, in particular in SSA where currently many principles of sustainable intensification are far from being fullfilled (Vanlauwe and Dobermann, 2020). Prioritizing a few important indicators and subsequent benchmarks can be done in a stepwise manner, e.g. by first considering farmers' and secondly governments' objectives. Maize self-sufficiency at household level and yields for national food self-sufficiency can be two such indicators. Focussing on maize in terms of energy alone however, only reflects the bare minimum to survive. Including the living income as a third benchmark, would ensure that basic human rights are considered, including a nutritious diet and social needs such as schooling. Increasing income to a living income however, will require larger structural changes (Chapters 2 and 4) and can therefore only be attained over a longer time span, e.g. >10 years. N use efficiency is a useful additional indicator for sustainable intensifying production (Zhang et al., 2015). Linking it to the yield indicator (minimum output benchmark) in the N use efficiency framework (EU Nitrogen Expert Panel, 2015) also ensures that aiming for adequate N use efficiencies does not come at the expense of low yields (Fig. 4.5). The indicators for maize self-sufficiency, maize yields and income (value of produce) however, may be prioritized over the N use efficiency indicator as they link to the basic human rights. Our results showed that the combination of these four indicators gave a good insight in some of the key constraints and trade-offs for sustainable intensification of smallholder farming systems. Hence, prioritizing and combining these indicators and their benchmarks can be used as first targets towards more sustainable farming systems.

6.3 Towards sustainable farming systems: increasing yields and farmer income

Chapters 3 and 5 both focussed on the relation between increasing the key indicators 'yield' and 'household value of produce from crops' (as estimate for income) and related this to cultivated area. Current small farm areas turned out to be limiting and thereby a key constraint for increasing household income towards the living income benchmark in the impact-oriented perspective (Chapter) 3. In the target-oriented perspective (Chapter 5) we therefore assessed what farm are would be required to attain a living income from crops given scenar-

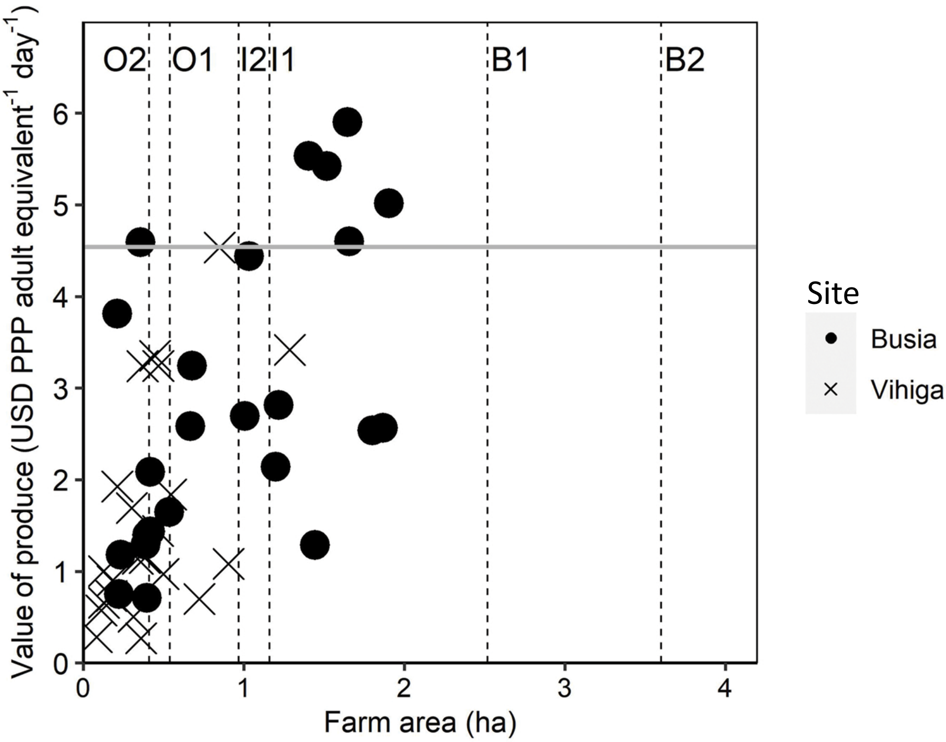

Fig. 6.2: Value of produce per household in relation to the farm area based on the results of Chapters 2 to 4 for Busia and Vihiga in western Kenya based on the 2017 data. The horizontal line indicates the living income. The vertical dashed lines represent the viable farm sizes based on the scenarios of Chapter 5 for Nyando, western Kenya. Full scenario names: *B1: baseline yields, B2: baseline yields - costs, I1: improved yields, I2: profitable crops, O1: livestock income, O2: off-farm income*.

6

ios that incrementally added crop intensification strategies and alternative income sources. These two perspectives are summarized in Figure 6.2. By combining the two perspectives in this thesis different options and changes emerged that are required to get towards a living income and desired yield levels. Here I will discuss these changes for the three farm production factors: land, labour and capital, while also considering knowledge as a fourth factor needed if cropping systems change, as described in Chapter 2.

6.3.1 Capital

Increasing available capital through a USD 100 input voucher immediately increased yields for all households in the impact-oriented perspective (Fig. 6.1). This highlights the importance of current capital constraints, or the poverty trap as we also called it, both for households with a small and a large cultivated area (Fig 4.1). Moreover, it highlighted that farmers' current knowledge and available technologies were sufficient to increase yields to 40-50% of the water-limited yield. Capital constraints are thus a key limitation in moving towards the favourable intensification scenarios of the target-oriented perspective (Chapter 5). Solving these constraints requires financial measures such as input subsidies or price subsidies. As discussed in detail in Chapter 5, agriculture, also in Europe or the US, has for a long time been subsidised and subsidies are used to ensure that farmers obtain a decent income (e.g. Van Merriënboer 2019; EU 2020). Input subsidies, price guarantees and other financial measures were also key for the success of the Green Revolution in Asia (Koning, 2017; Wiggins, 2016). Policy measures that directly alleviate capital constraints for farmers may thus be inevitable and a relatively easy measure for the necessary yield increases in SSA.

6.3.2 Knowledge

We found that farmers' current knowledge was limiting for the more complex changes in the impact-oriented perspective (Chapter 2), which poses a challenge as these changes are required for sustainable intensification and therefore also required more favourable (sustainable) intensification scenarios in the target-oriented perspective (Chapter 5). These were both changes related to agronomic knowledge (e.g. changing legume intercropping systems) and farm management knowledge on decisions or so called 'strategic choices' (De Koeijer et al., 2003). These new strategic choices emerged as available capital increased, and thereby productivity, resulting in a change in farmers' production objectives: from attaining maize self-sufficiency towards attaining a better income. These changes in production objectives however, were slower than expected and farmers also continued to prioritize maize self-sufficiency (Chapter 3), possibly due to earlier experienced scarcity. The production objective to be self-sufficient has formed over a longer time and may again change over a longer time, i.e. over a period of perceived abundance. Co-learning may speed up this process, but still take time (Chapter 2) and is difficult to scale out. Less time demanding options such as SMS messages or other IT-based solutions are therefore required for influencing these strategic choices over multiple seasons.

Farmers in western Kenya may also require new knowledge if maize yields would have to increase beyond 50% of the water-limited yield. For instance new commercially available maize varieties have higher yields than common current varieties, but are not adopted (One Acre Fund, 2016). This may be due to the limited experiences farmers have with these new varieties, making them choose the varieties of which they know the performance on their farm, as was observed during co-learning workshops. Improving yields with increased fertiliser application also requires increased planting densities, which has been tested on a limited scale with modern varieties in Kenya (Cropnuts, 2019; One Acre Fund, 2019). Further research on the interaction between altitude (rainfall and temperature), fertiliser application rates, different modern varieties and planting density would be required to generate such an advice that can be used by farmers.

6.3.3 Land

Land, labour and capital can partly be interchangeable (Hayami and Ruttan, 1971). This needs to be taken into account when incentivising production increases. In Chapter 3, as a result of the impact-oriented perspective, we found that farmers increased their cultivated area with the introduction of the input voucher, mainly by renting-in land. For households with a small farm area, increasing the farm area is required to get to a decent income (Chapter 3 and 5). At landscape level however, increasing farm area into natural areas is not desirable (Baudron and Giller, 2014). Increasing land area also goes against key principles of sustainable intensification, increasing output per unit land and per unit input (The Montpellier Panel, 2013; Tilman et al., 2011). In Box 6.1., however, I highlight that increasing land area can result in larger production for an individual farmer, while running a smaller risk compared to intensifying input on a smaller farm area, using a back-of-the-envelope calculation from a farmers' perspective. This can explain why farm area also increased for those with an already larger farm area (Chapter 3) and application rates remained relatively low (Chapter 4). Increasing crop yields is therefore not always favourable from a farmers point of view (Silva and Ramisch, 2018; Sumberg, 2012). In Chapter 5 however, intensification was a favourable scenario, as it led to a relatively small viable farm size, meaning that more households could attain a living income from the available land. This would thus be beneficial from a landscape or national perspective. Policies are therefore required that, on the one hand, make increased input-use attractive for farmers, such as input subsidies, crop insurances and prices guarantees, while on the other hand the increase in farm area at landscape level should be limited to ensure the protection of areas that are important for biodiversity (Giller et al., 2021).

Box 6.1. Increased mineral fertiliser use: using a higher rate or spreading it on a larger area?

What follows here is a simple, back-of-the-envelope type of calculation. We have a typical farm in western Kenya on which 0.4 ha of maize is cultivated. The farmer usually applies about 50 kg N ha^{-1} by applying 50 kg of DAP at planting and 50 kg of CAN as topdressing on the 0.4 ha. Through the USD 100 input voucher of the integrated co-learning programme s/he can obtain another 50 kg of DAP and 50 kg of CAN, costing together USD 54, leaving the remainder of the voucher for seed and other inputs. The question that now arises for the farmer, is whether to use this fertiliser as additional fertiliser, which results in an application rate of approximately 100 kg N ha^{-1} and which fits the agro-ecological potential of western Kenya, or to expand the farm area. Renting an additional 0.2 ha costs around USD 20 $seasons^{-1}$. S/he could then use the remaining USD 34 (of the USD 54 that he would normally spend on fertiliser) for fertiliser and seed and apply the usual rate of 50 kg N ha^{-1} on all fields.

The table below summarized the two options for the farmer and gives the yield estimates that were generated using the QUEFTS model (Janssen et al., 1990; Sattari et al., 2014). Although yields are higher with the increasing N application rate-option then with the increasing maize area-option (3794 vs. 3386 kg ha^{-1}), total production is 510 kg higher with the increasing maize area-option, totalling 2030 kg. Expanding the maize area may thus be beneficial for the farmer in terms of total production. Moreover, applying a lower rate results in a lower risk for yield losses during poor seasons. Increasing the area of maize however, will require more labour inputs. Moreover, this calculation was based on current cost of land in Busia, western Kenya. Outcomes of such a calculation may differ in places where rental prices are higher due to land scarcity (Chamberlin et al., 2014).

Table: Total maize grain production at farm level for two options to increase production.

	Increasing N application rate	Increasing maize area
N application rate (kg ha^{-1})	100	50
Area (ha)	0.4	0.6
Yield (kg ha^{-1}) [1]	3794	3386
Production (kg)	1520	2030

[1] Yield estimates were calculated using QUEFTS with using median soil variables for Busia, which were derived from soil samples taken in farmers' fields that were part of the integrated co-learning approach: pH, 5.7; SOC, 1.5%; total N, 0.1%; P-Olson, 5.2 mg kg^{-1}; and exchangeable K, 19 $mmol_{(+)}$ kg^{-1}.

6.3.4 Labour

In this thesis, no direct attention was given to labour and possible labour constraints at farm level. However, in Chapter 4 we found indications for labour availability limiting crop choice. Groundnut, which can generate a higher value of produce per ha than maize, was not attractive for farmers with a larger farm area because of its higher labour demand than maize, both for harvesting and threshing (Chapter 4). This indicates that labour saving technologies may be needed when moving to future farming systems in which farm areas would increase and/

or diversify. Then, options like two-wheeled tractors (Aune et al., 2019; Baudron et al., 2015), would be needed to relieve labour constraints. Mechanization could be supplied by service providers owning a tractor (Van Loon et al., 2020), which is common with four-wheel tractors in northern Ghana (Diao et al., 2014).

6.4 Methodological considerations

6.4.1 Main methodological contributions

In Chapter 2 a novel integrated co-learning approach was presented, comprised of four complementary elements: input vouchers, an iterative learning process, common grounds for communication, and complementary knowledge. It build on a range of earlier participatory approaches (e.g. Defoer 2000; Carberry et al. 2004; McCown et al. 2009), while the inclusion of an input voucher was new. The voucher resulted in new learning experiences, both for farmers and researchers, which could be capitalized using the other three complementary elements of the approach. Moreover, testing the approach over five seasons as a farm level experiment, including detailed monitoring of farm management and yields, can also be seen as an addition to the tools of farming systems analysis, which were described by Descheemaeker et al. (2019).

The detailed data collected, as part of the farm level experiment in Chapter 2, allowed for further household level analysis. In Chapter 3 I combined the notion of yield gap closure with the living income benchmark for household income. The living income benchmark has recently been adapted for smallholder farming systems that include staple crops (van de Ven et al., 2020). I applied it for the first time to such detailed household level data. Combining these two approaches highlighted the limited benefits smallholder farmers had when yield gaps were closed to desired levels, mainly due to the small farm size.

In Chapter 4 I used the multi-season data of the farm level experiment for a multi-criteria analysis, which gave a comprehensive insight in the development over time of key indicators for sustainable intensification. Analysing these indicators over multiple seasons allowed for identifying possible pathways that can lead towards sustainable intensification. Diversification towards more legumes in the cropping system, for instance, took multiple seasons and was not a linear process (cf. Pinch and Bijker 1987). Applying such multi-season studies may thus be key in adoption studies of new technologies (Glover et al., 2019) or in assessing possible incentives towards pathways for sustainable intensification.

Chapter 3 showed the need for analysing what farm area would be required to attain a living income. In Chapter 5 we therefore developed the ‘viable farm size’ concept: the cultivated area required to attain a living income from farming. Comparing the viable farm sizes with the current distribution of farm sizes indicated which part of the current farming population could attain a living income from farming in the various scenarios. An interactive tool or game that summarizes our findings could be used with stakeholders in so called 'backcasting studies' (Holmberg and Robért, 2000; Quist and Vergragt, 2006), to assess what step-by-step changes in farming systems would be required for all farming households to attain a living income by, e.g. 2040. An intermediate goal could then be e.g. maize self-sufficiency. Implications on the alternative employment opportunities, required for those going out of farming, should also be considered in such a tool. Other applications of the viable farm size methodology could be to inform governments on effective measures for farmers to make a decent living, as is done in the European Union (EU, 2020). Future research is also needed on the available crop land in rural areas in relation to (protected) natural areas. This can then be related to the current population in farming, to assess which part of the population can attain a living income from farming while maintaining important areas for biodiversity. And, maybe more importantly, for which part of the population alternative employment would be required, also considering the growing population in SSA. To further advance the viable farm size methodology, livestock land use requirements and its options for sustainable intensification should be included, similar to the current crop intensification scenarios.

6.4.2 Detailed farm level experiments to assess the impact of interventions

In Chapters 2 to 4 we used a 'detailed farm level experiment' as new method to assess impact of interventions at farm level, in our case the integrated co-learning approach. It build on the detailed farm characterization approach (see Tittonell 2008, Figure 4; and Giller et al., 2011), which is used in farming systems analysis to make a qualitative and quantitative description of the farming system (Descheemaeker et al., 2019; Giller et al., 2011). Testing the integrated co-learning approach through a detailed farm level experiment provided an insight into the future. It studied the 'what would happen if...' type of questions, in this case: what would happen if an extension and subsidy scheme was setup that includes a USD 100 input voucher per season, either with or without co-learning intervention. The detailed data allowed for getting a good understanding of farmers' choices and management outcomes. It also gave a realistic insight in the effects on farmer income. This type of detailed farm level experiments could thereby also be applied to similar research questions e.g. on the impacts of subsidized prices , crop insurance, subsidised input use, increasing availability of new varieties and/or providing credit inputs.

Such detailed farm level experiments however, require skilled and experienced field researchers and longer term engagements in a locality. We were lucky to have a field assistant who had over 10 years of experience working with farmers on similar projects in the area. Together with the experienced field station manager (>15 years) of CIAT, Maseno, they were key in informing the co-learning activities. For instance on which varieties work in which areas or what could be alternative legume options (e.g. groundnut). Such information was hard to find from (grey) literature and may indeed require experience and multiple years of engagement in an area, something that seems difficult to support given the short term duration of many projects.

6.4.3 Detailed farm characterization vs. rapid baseline surveys

This thesis was based on two contrasting types of primary data. Chapters 2 to 4 were based on detailed field and farm level data collected over five seasons. Chapter 5 was based on one-off survey data from the RHoMIS survey (Hammond et al., 2017), which we used for scenario analysis. Both types of data are common in farming systems analysis (Descheemaeker et al., 2019). The differences in level of detail, assessment methods and numbers of households involved however, make these two contrasting data sources with both their own use and limitations.

Detailed farm characterization methodology usually starts with a rapid farm characterization survey (20-30 minutes) that focusses on farm structure and production objectives and other indicators commonly used for developing farm typologies. This is then followed by a detailed farm characterization that involves multiple visits of 1-2 hours per visit with a limited number of households (e.g. 20) that represent the diversity of households found in the rapid farm characterization survey (Giller et al., 2011; Tittonell, 2008). The RHoMIS survey aims to get a snapshot of the wellbeing of a rural household, including poverty, nutrition and income related indicators, within a relatively short time (40-60 minutes). This is longer than the rapid farm characterization surveys, but definitely more rapid than the common large scale surveys such as the IMPACTlite survey (Rufino et al., 2013) and the LSMS survey (The World Bank, 2021). Farmer reported survey data however has limited accuracy and precision (Fraval et al., 2019). This is one of the reasons why detailed farm characterization uses mixed methods (e.g. combining farmer reported data, observations and measurements) and triangulation (Giller et al., 2011). In our case, the RHoMIS survey data gave a quick overview of current farm sizes and household income distributions within each site. Our next questions, however, went more in detail on the cropping system and resulted in a number of difficulties on estimating farm sizes and yields, indicating some of the limitations of rapid one-off surveys.

Current farm sizes in Chapter 5 were clearly linked to multiples of an acre (Fig. 5.6), again indicating the limitations of farmer reported farm area instead of measured farm areas (Carletto et al., 2013; Gourlay et al., 2017). Moreover, farmers often do not report all their land in a first visit or one-off survey. Only after the third season farmers reported no additional fields anymore that were already theirs in previous seasons in Chapter 3 (Fig. 3.3). This again highlights the need to build trust with farmers, e.g. over multiple visits, for getting a comprehensive insight in a farming system.

The choice in the RHoMIS survey to ask all questions per crop per year, instead of per field and per season, proved too much of a simplification for agronomic and farm management related research questions. It reduces the time spent taking the survey, but means that a farmer needs to make the difficult estimate of which fraction of the total farm area is cultivated per crop per year (Supplementary materials 5.3). These estimates of crop area fractions per year also hampered basic agronomic calculations like calculating yields per ha and per season (Chapter 5). Information per crop per year therefore at best results in a first impression of total production and income from crops per year. More detailed approaches are needed to answer questions related to farm management and yields, e.g. similar to the detailed farm characterization approach. We should therefore be careful not to make the same mistake as where Van Asten et al. (2009) warned for; in their case doing too rapid participatory research, or in our case, doing too rapid rural surveys for goals that they were not designed for.

6.4.4 Integrated co-learning as a tool for testing and scaling out new technologies

The integrated co-learning approach, with farmers taking part in farm level experiments, can also be used for testing and scaling out new technologies. It can be one of the steps in the sequence from fully controlled 'on station' research until the step that farmers start to try out a new technology (Fig. 6.3). As such, it can be comparable with the 'pilot farms' described by Vereijken (1997), who try out the new technologies which were found successful on a 'prototype farm' and links to farmer 'try outs' described by Misiko and Tittonell (2011). The prototype farm is fully managed by researchers, mimics local farm structure (farm area, labour) and can be used to optimize for specific objectives (Vereijken, 1997), e.g. N use efficiency in the Netherlands (Aarts et al., 2000). Examples are 'de Marke' in the east of the Netherlands (www.demarke.eu), or early on in Zimbabwe (Rodel and Hopley, 1973). Pilot farms on the other hand are fully farmer managed. As such, pilot farms may have limited strength in determining agronomic principles due to enormous variation at field level within and between farms. We could for instance not find a relation between N application rates at field level and yield (not shown). The small number of farms studied often also do not make it feasible to do statistical analysis at farm level. The strength of pilot farms, however, lies in testing a technology under real farm conditions. It can lead to so called localized applications of technologies (Descheemaeker et al., 2019) and ensure it is tested among a diversity of farmer socio-economic and biophysical (e.g. soil type) conditions (Vereijken, 1997). A voucher or other incentives should probably be included for pilot farmers in SSA to ensure that socio-economic constraints are somewhat released and farmers are able to try out the technology. The size of the incentive, however, should depend on whether the aim is to test technologies under full current conditions or under future conditions which include, e.g. a voucher. Integrated co-learning, in a scheme of prototype and pilot farmer could thereby also be a tool to improve the 'scaling readiness' of a technology (Sartas et al., 2020). Setting up such a scheme, however, would require long term engagement of for instance national governments through their national research organizations and/or of CGIAR institutes. 'De Marke' and its pilot farms, however, showed that such long term engagements are key for tackling complex challenges such as more efficient N use in the Netherlands or increasing yields and farmer incomes in SSA.

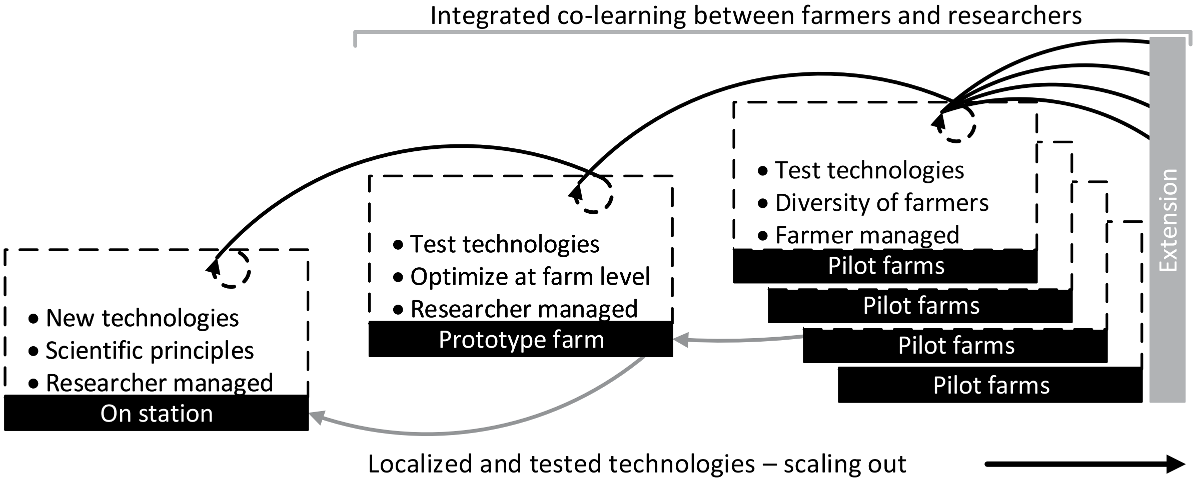

Fig. 6.3. A process diagram of the integrated co-learning approach being part of a system of prototype and pilot farms. The (grey) arrows indicate the constant need for feedback between farmers and researchers. The circular arrows in each farm indicate moments of evaluation of a technology.

6.4.5 Other considerations on the methodology and future research

The objective of Chapters 2 to 4 was to assess the impact of the integrated co-learning approach. The voucher was included to test whether capital is currently a main limitation for farmers to increase their farm level production and assumed some sort of continuous financial support is required for farming. Continuous support, however, may not always be feasible. In this thesis I could not answer the question of what happens after a period of five seasons of increased input use through integrated co-learning. Did this set a 'flywheel' in motion for some farmers, allowing them to continue or even increase their input use? Or did they continue at a lower level and possibly even went back to their original input use and productivity level? To answer this question, a follow-up study with the participating farmers, e.g. five seasons later, could be done. This can shed a light on the reasons why farmers continued, or not, to maintain the intensification level achieved during the programme.

In Chapters 2 to 4 we focussed on western Kenya. Current fertilisers input use in Kenya, however, is more common than in many other countries in SSA. Fertiliser use is for instance much lower in neighbouring Uganda (Sheahan and Barrett, 2017). Farmers in Kenya also already had varying experiences with using improved seed in our co-learning groups. Using the integrated co-learning approach in other countries where knowledge of farmers on fertiliser use is more limited than in Kenya, like e.g. Uganda (Pincus et al., 2018), would possibly require more time and therewith result in slower yield increases. In such places, also a larger effect may be expected of the workshops on the input choices, than what we found in western Kenya, see Chapter 2 (Fig. 2.7).

6.5 Concluding remarks

In this thesis I studied some of the key challenges that smallholder farming face in SSA: low yields, low incomes and small farm sizes. At national level, agricultural production needs to increase to keep pace with burgeoning population. The UN Sustainable Development Goals have as key principle 'to leave no one behind', while many of its goals are related to sustainable development of rural livelihoods. This thesis highlights the difficulty of reaching the multiple goals at multiple levels of sustainable development of farming systems and highlights that attaining some goals may be easier to attain than other goals.

One of the goals at national level can be to reach 50% of water-limited yield to reach a level of food self-sufficiency by 2050 (van Ittersum et al., 2016). We found that current maize yields for farmers in western Kenya were mainly limited by financial constraints as maize yields immediately increased from less than 20% to 40-50% of the water-limited yield with the provision of a US$ 100 input voucher per season. With this yield increase, most households became maize self-sufficient, which was their primary production objective, but it was not enough to meet other aspirations such as a nutritious diet and schooling, as covered by the living income. At best 30% of the households obtained a living income from the value of crop produce in the site with the largest farm sizes (Busia) while this was almost none in the site with the smallest farm sizes (Vihiga). Value of crop produce seemed mainly limited by current farm area. Although one-third of the households increased their farm area, this was not enough to obtain a living income. This was confirmed in Chapter 5, in which we developed the 'viable farm size' concept: the cultivated area required to attain a living income from farming. We found that intensification to 50% of the water-limited yield will not lift all households out of poverty and additional measures such as increased farm area, further intensification and/or other sources of income will be required. This is an important message to governments and other policy makers. Further research could therefore include using the 'viable farm size' concept as a tool in back casting activities with (local) governments and other stakeholders. Moreover, the 'viable farm size' benchmark can be used in studies assessing how smallholder farmers can attain a living income from farming, as a step towards more sustainable farming systems.

Other goals of sustainable intensification, besides increasing maize yields, proved more difficult to attain. N use efficiencies remained too high (risk of soil mining) and many farmers increased both their farm and maize area, while applying relatively low N rates. These indicator outcomes pointed towards pathways of extensification instead of the preferred pathway of intensification. Facilitating sustainable intensification may therefore require incentives that increase input use (e.g. input subsidies, crop insurance, price subsidies), measures to ensure input use per unit land reaches desired levels and regulations to avoid that cultivation expands into areas that are important for biodiversity. This requires further research on how and what measures can be used to incentivise sustainable intensification. The 'detailed farm level experiments' that were used in Chapters 2 to 4 can be a useful research tool for getting a detailed understanding on farmer responses and management outcomes of possible new policies such as crop insurance or price subsidies.

The integrated co-learning approach that we developed as part of this study proved key for some of the more complex changes that were required for sustainably intensifying the farming systems and to adapt technologies to the local context. Incorporating the integrated co-learning approach in a system of prototype and pilot farms could be a way to further develop the approach and make it part of local research and extension.

To conclude, this thesis highlights the large scale changes and investments required for smallholder farming. The diversity in responses (Chapters 2 to 4) and diversity in current farm sizes (Chapter 5) further compound this challenge. Reducing the poverty trap, in which many smallholder farmers currently operate because of capital and farm area constraints, may therefore be a first necessary step towards sustainable intensification of smallholder farming systems and *leaving no one behind*.

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Supplementary materials 2.1

Issues and questions raised by co-learning group farmers during evaluation interviews following 2016 short rains cropping season. I is an issue mentioned, Q are questions raised by participants.

Vihiga (n = 12)	%	Busia (n = 11)	%
I./Q. How to handle drought	73	I./Q. How to handle drought	67
I. Rodents in soybean	64	Q. Control striga (+if no manure)	42
Q. Control striga (+if no manure)	36	Q. How to control termites	33
Q. Soya for dry season?	27	I. Feed shortage dry season	25
Q. Understand soil fert. gradients	27	Q. Understand soil fert. gradients	25
Q. How to control termites	18	Q. Mz/Sb intercrop or rotate	25
Q. Why does banana die? (BXW[1]?)	18	Q. Sorghum for very dry seasons	17
I. Animals not used to dairy meal	18	Q. Soybean varieties for very dry seasons	17
Q. What if no manure available, ISFM[2]?	18	I. Time it cost to sell milk	17
Q. What fert. to app. at what moment?	18	I. Grain storage	17
Q. How to rehab. non-responsive field?	18	Q. How to do rotation	8
I. Erosion	9	Q. Short duration beans	8
I. Lodging by wind	9	Q. What are best planting depths	8
Q. How to do poultry farming?	9	Q. What are best planting densities	8
I. Moles	9	I. Moles	8
I. Feed shortage dry season	9	Q. Value addition in soybean	8
Q. Holes or furrows for planting?	9	Q. Marketing of soybean	8
Q. Need to know about food security	9	Q. Manure handling	8
Q. What are the best maize varieties?	9	Q. Need to know about food security	8
I. Beans are eaten by animals	9	Q. Value addition milk	8
		I. East coast fever (cows)	8
		I. Ticks	8
		I. Veterinary services	8
		I. Quality of dairy meal	8
		I. Pests in soybean	8

[1] Banana Xanthomonas Wilt disease,

[2] Integrated Soil Fertility Management

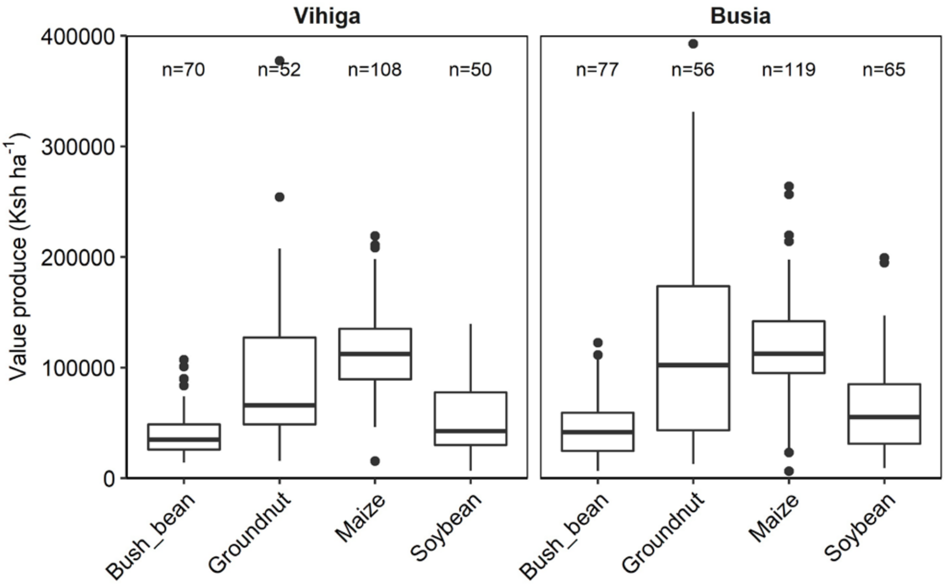
Supplementary materials 2.2.

Answers given to the question “What was the most useful of what you learned during the programme?”, which were used as input-data for Fig. 2.5.

	Location		Answers
	Vihiga	Busia	
Comparison farmers			
		1	Timely planting
	1	2	Use of hybrid maize seed
	1	1	Sufficient fertilizer use in maize
		1	Timely availing inputs
		1	The use of legumes for the household
	3	2	Combining mineral fertilizer and hybrid maize seed
		1	Combining manure and mineral fertilizer for maize
	1		Combining timely and adequate inputs wit hybrid maize
	4	3	Combining, and sufficient use of, mineral fertilizer and hybrid maize seed
	3	1	Combining, and sufficient use of, mineral fertilizer, hybrid maize seed, and having it timely available
Total	*13*	*12*	

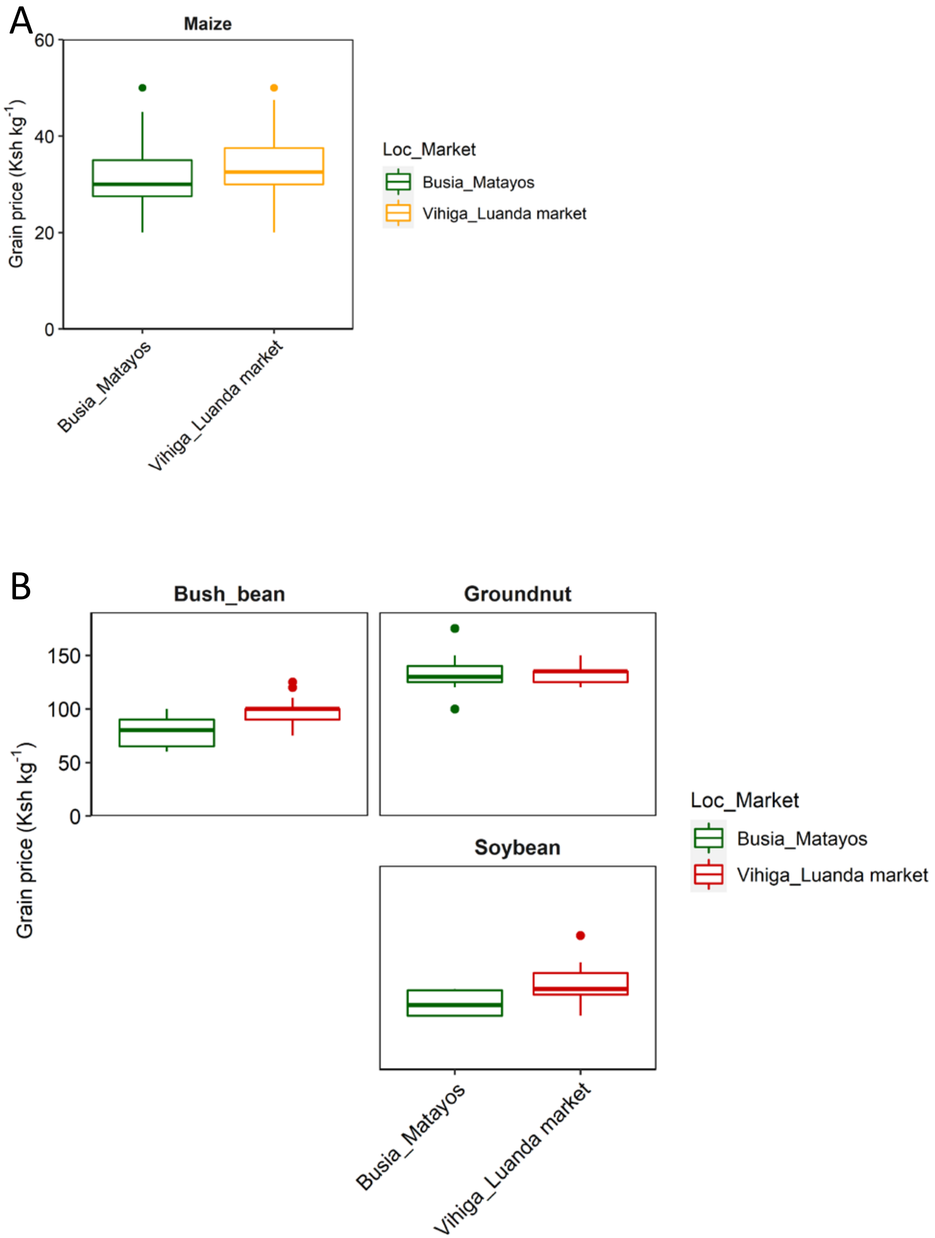
	Location		Answers
	Vihiga	Busia	
Co-learning farmers			
		1	The use of legumes in the farm
	3	1	Combining manure and mineral fertilizer for maize
		1	Using sufficient mineral fertilizer and correct rates
	1		Combining hybrid maize seed with soybean-maize rotation
	1	2	Combining and evenly spreading manure and mineral fertilizer across the farm
		1	Combining manure, mineral fertilizer and crop rotation
		1	Combining even application of mineral fertilizer, returning crop residues to the field and using hybrid maize seed
		1	Combining and evenly spreading of manure and mineral fertilizer across the farm
	4	1	Combining manure, mineral fertilizer and hybrid maize seed
	1		Combining mineral fertilizer, hybrid maize seed and proper spacing
	1		Benefits of pure stand groundnut and soybean: profitable, residual effects on maize and no smothering by maize
	1		Combining manure, mineral fertilizer and hybrid maize seed as part of mbili-mbili intercropping with legumes
	1		Combining manure, mineral fertilizer and hybrid maize seed in soybean-maize and groundnut-maize rotation
		1	Combining manure, mineral fertilizer, hybrid maize seed, correct spacing and timely planting
		1	Combining and evenly spreading manure and mineral fertilizer across the farm, hybrid maize seed, correct spacing and timely planting
		1	Controlling striga through combining: soybean-maize intercropping, pulling emerging striga, combining manure with mineral fertilizer, using IR-maize, and planting in lines when intercropping (spacing)
Total	*13*	*13*	

Supplementary materials 3.1



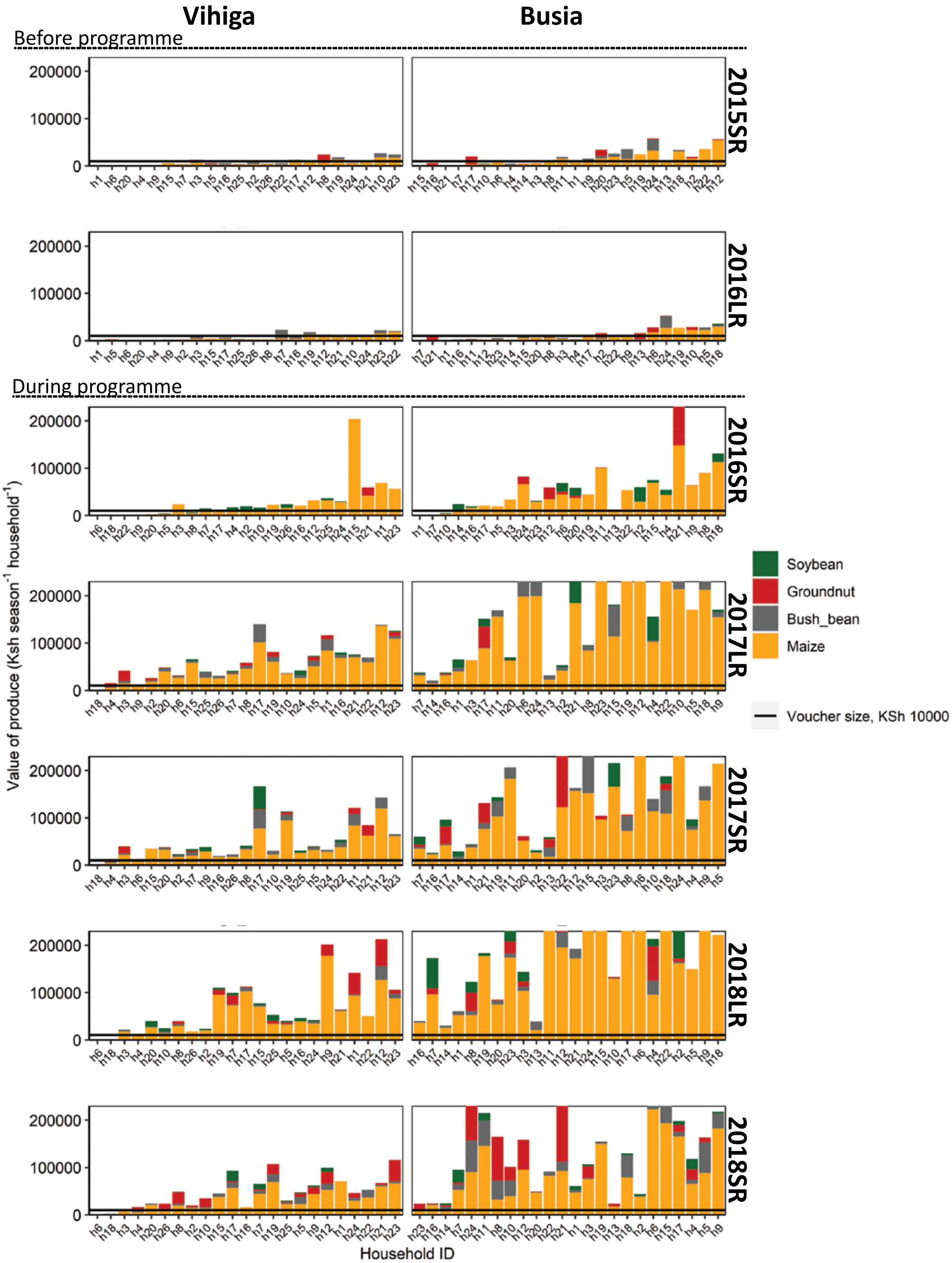
Value of produce per ha per crop per household for all seasons that were part of the programme.

Supplementary materials 3.2



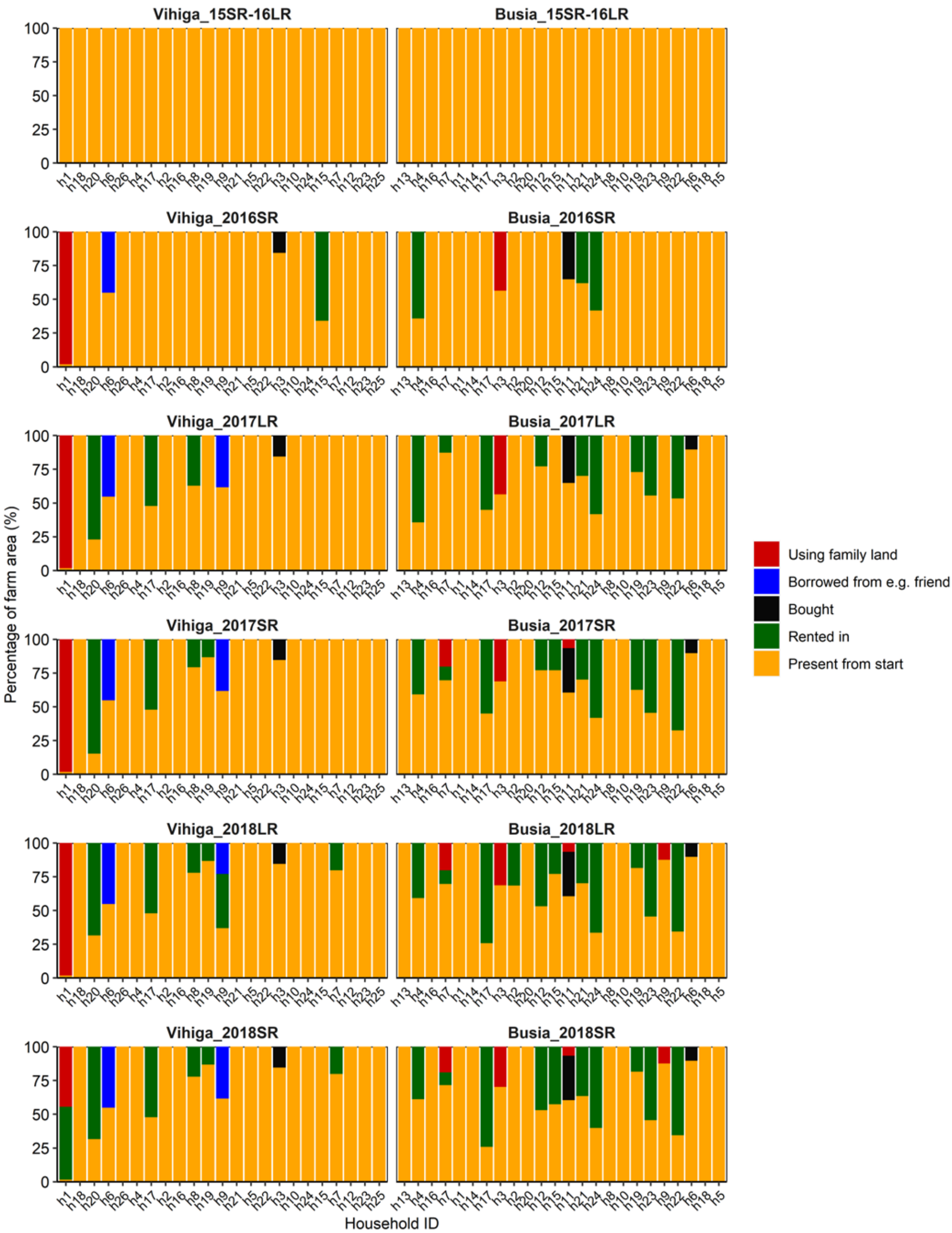
Grain prices in 2018 for maize (A) and bush bean, groundnut and soybean (B) based on weekly price observations in Busia (Matayos market) and Vihiga (Luanda market).

Supplementary materials 3.3



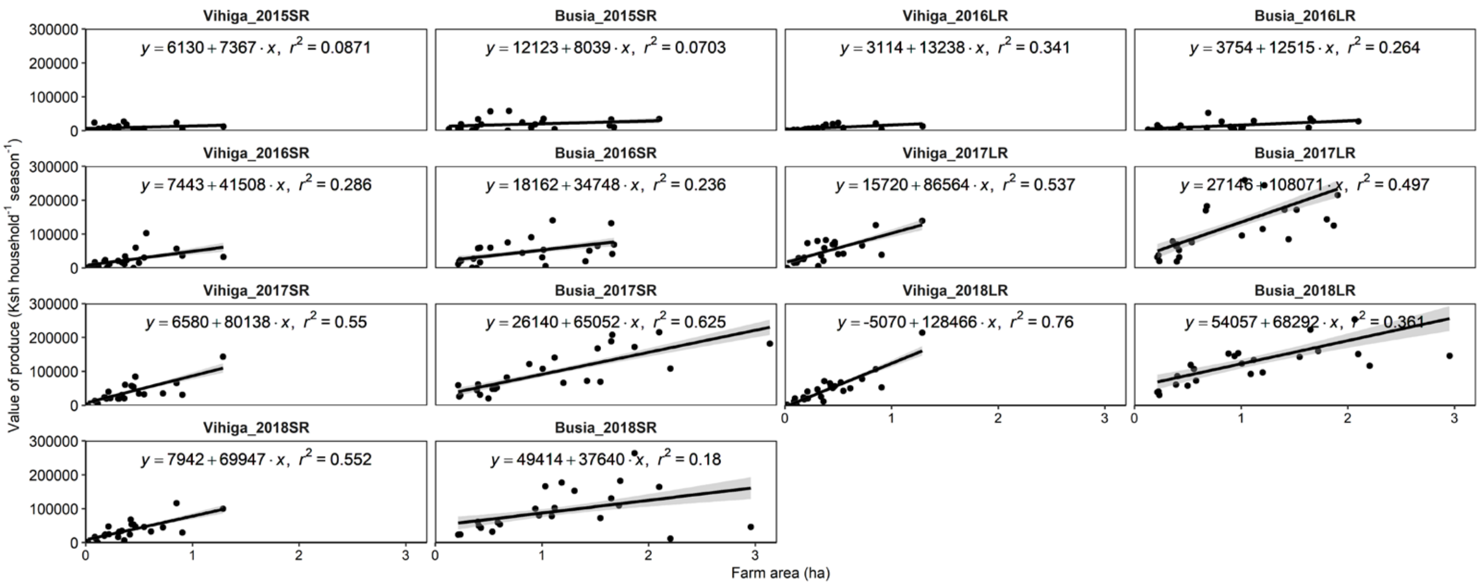
Total value of produce (Ksh) per household per season. Households are ordered according to their value of produce per adult equivalent per day as shown in Fig. 3.2. Differences in order are therefore caused by the household size per household, that was used to calculated the adult equivalents per household.

Supplementary materials 3.4



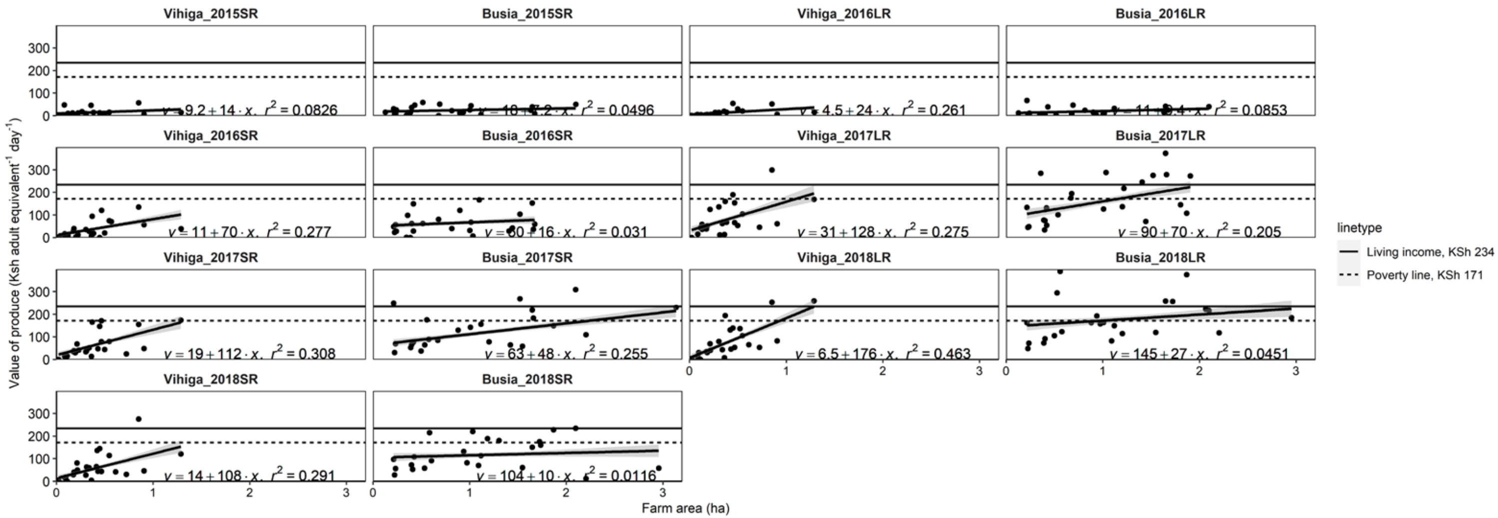
Additional farm area and farm area present from the start as percentage of the total farm area per household per season. Households were ordered according to their initial farm area in 2016SR, see also Fig. 3.3.

Supplementary materials 3.5



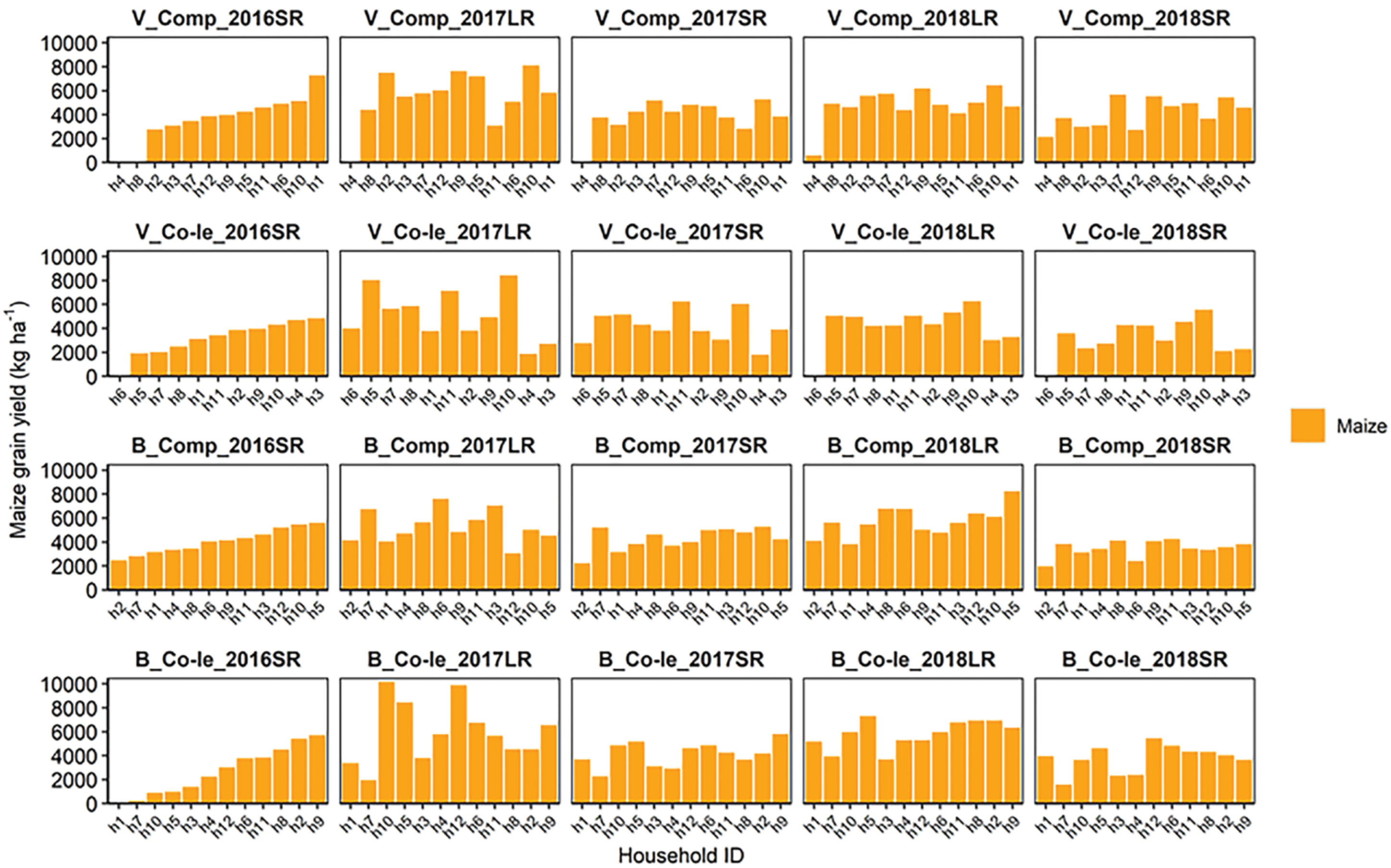
Value of produce per household per season in relation to farm area. Seasons 2015SR and 2016LR were before the programme while the following seasons were during the programme.

Supplementary materials 3.6



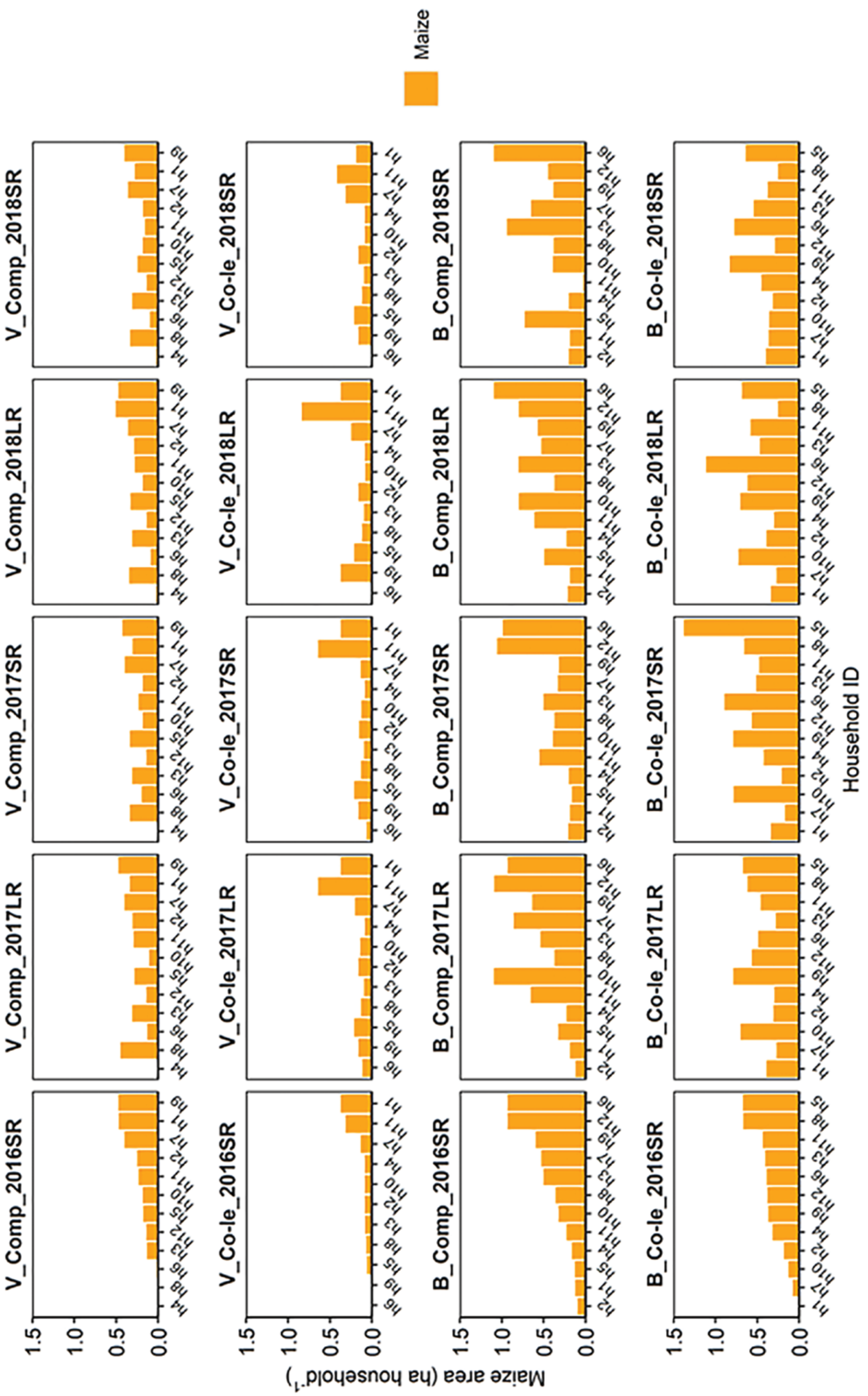
Value of produce per adult equivalent per day in relation to farm area for all seasons. Seasons 2015SR and 2016LR were before the intervention while the following seasons were during the intervention.

Supplementary materials 4.1



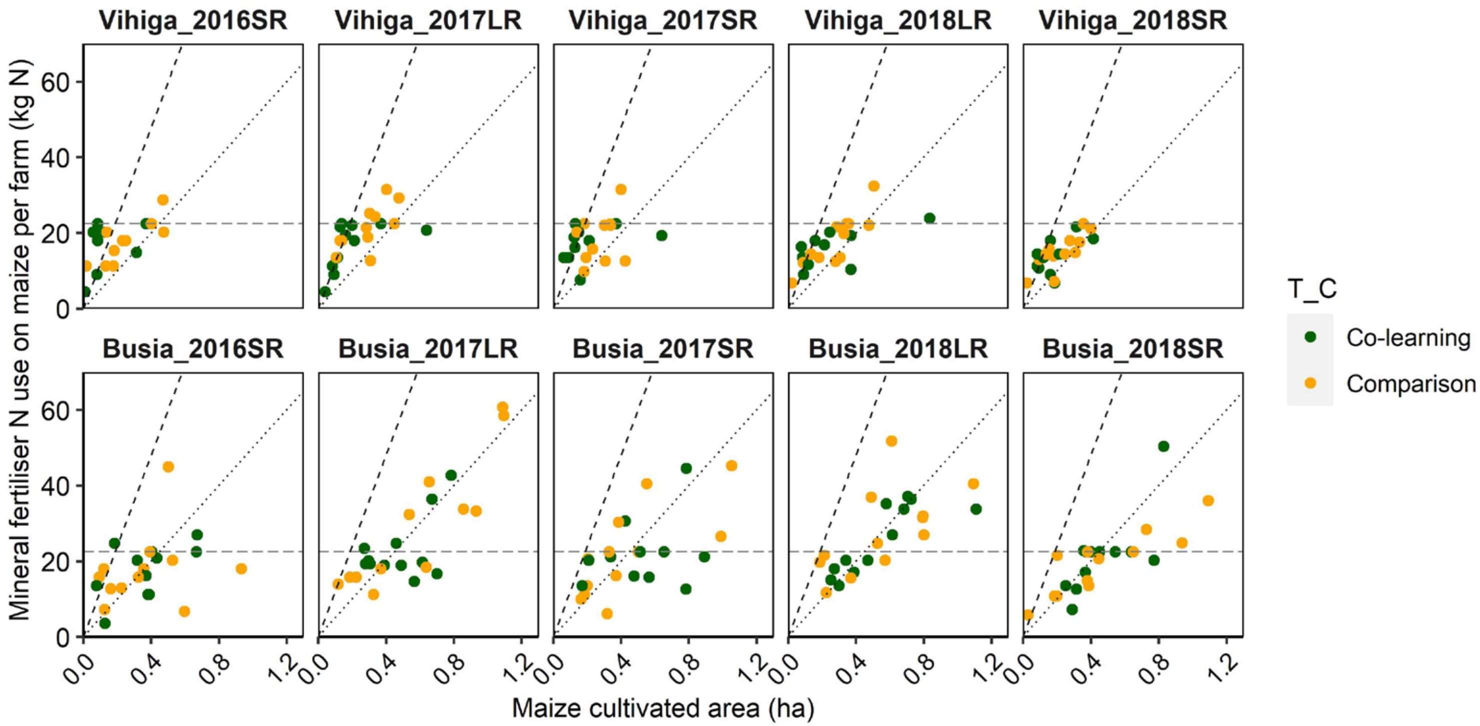
Household average maize grain yield. Households were ordered according to their maize grain yields in 2016SR.

Supplementary materials 4.2



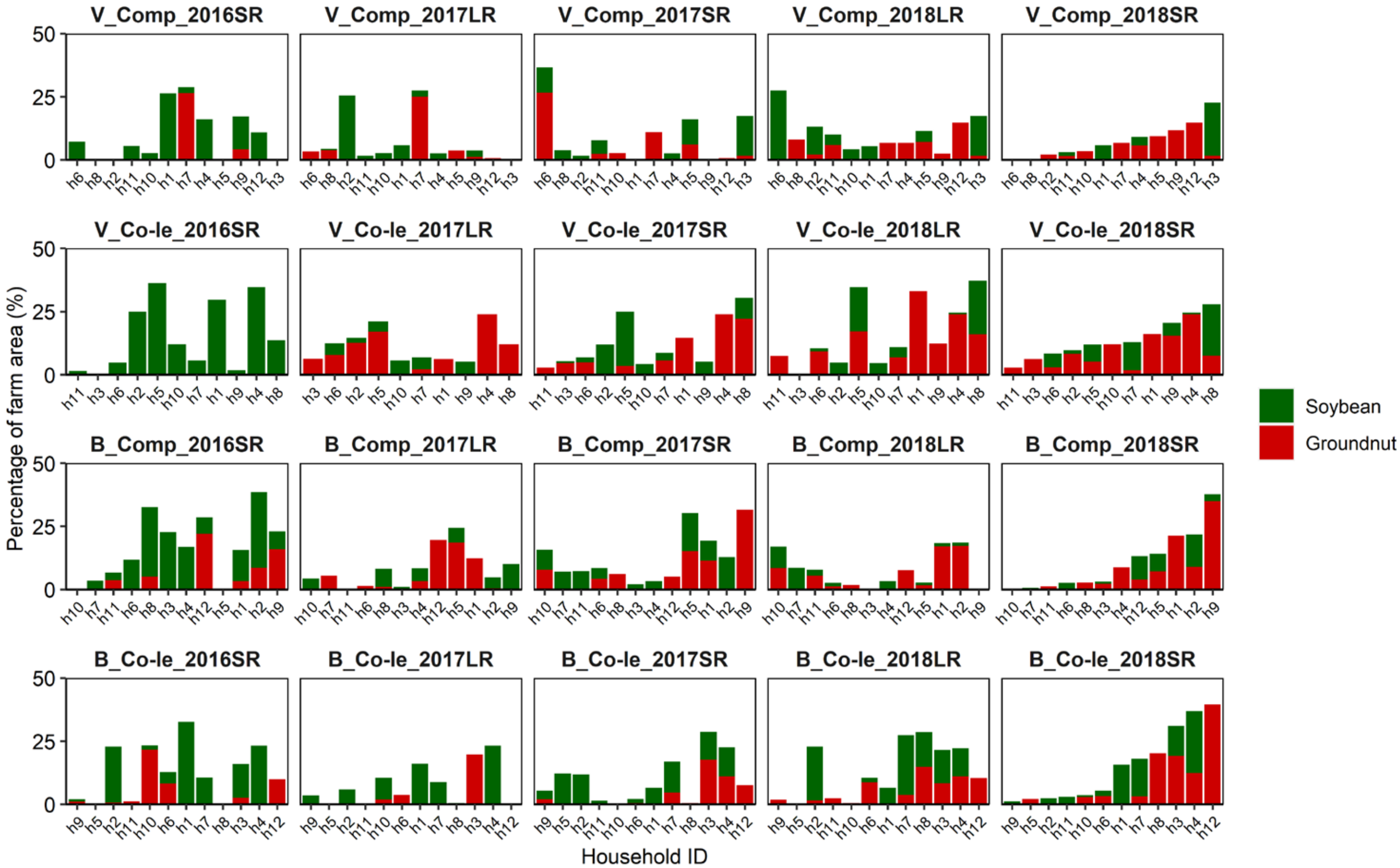
Maize cultivated area per household. Households were ordered according to their maize cultivated area in 2016SR's.

Supplementary materials 4.3



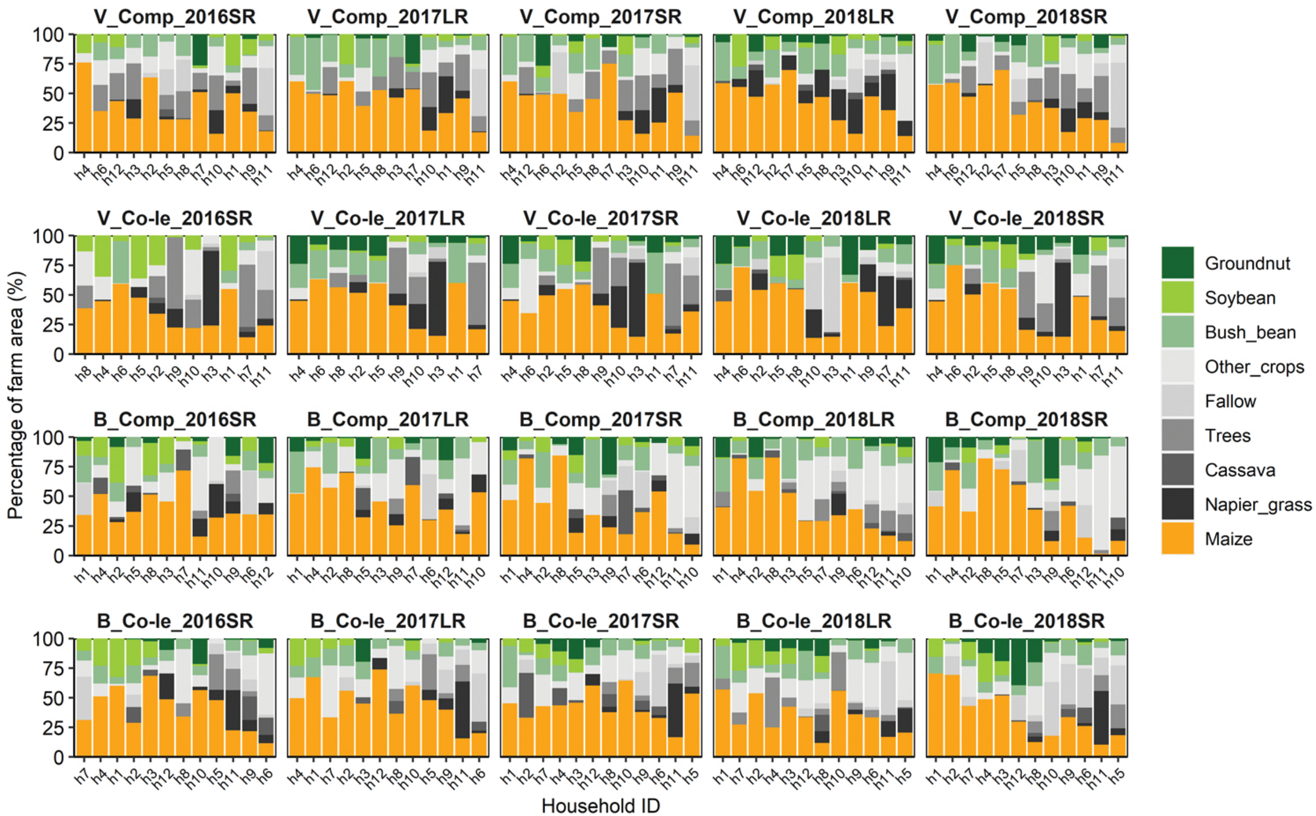
Mineral fertiliser N use on maize per farm in relation the maize cultivated area. The grey dashed line indicates an application rate of 120 kg N ha^{-1} which was the highest advice in the workshops. The grey dotted line indicates an application rate of 50 kg N ha^{-1} which is the advised application rate by One Acre Fund. The horizontal dashed line, at 23 kg N, indicates the amount a farmer could get when choosing one 50 kg bag of DAP and one 50 kg bag of CAN, spending 60% of the voucher on mineral fertilisers for maize.

Supplementary materials 4.4



Fraction of farm area with groundnut and soybean per household. Households were ordered according to their total fraction of groundnut and soybean together during the 2018SR season.

Supplementary materials 4.5



Percentage farm area per crop for all individual households, with households ordered according to their farm area per season, from small to large. Household ID's were assigned per location. All crops were corrected for their percentage intercropping with other crops per field to scale to 100%. All crops were included that were planted on at least 5% of the farm area on average across seasons in one of the sub-locations, with remaining crops being grouped as 'Other crops'.

Supplementary materials 5.1

Crop prices derived from the survey and from literature. Prices in bold were used for the analysis.

Region	Crop	Median price survey data (USD PPP/kg)	Price literature (USD PPP/kg)	
Nyando	maize	**0.71**		
	beans	**1.25**		
	sorghum	**0.57**		
	sugarcane	**0.06**		
Rakai	maize	1.54	**0.80**	Own data, living income survey 2017, van de Ven et al., (2020)
	maize	1.54	**0.80**	Own data, living income survey 2017, van de Ven et al., (2020)
	beans	3.17	**2.01**	Own data, living income survey 2017, van de Ven et al., (2020)
	beans	3.17	**2.01**	Own data, living income survey 2017, van de Ven et al., (2020)
	Irish potato	1.43	**0.80**	Own data, living income survey 2017, van de Ven et al., (2020)
	Irish potato	1.43	**0.80**	Own data, living income survey 2017, van de Ven et al., (2020)
	banana	0.27	**0.16**	Own data (unpublished) and Wairegi and van Asten (2010)
	cassava	**0.39**		
	coffee	0.80	**1.61**	Calculated from https://ugandacoffee.go.ug/monthly-reports?field_month_year_value%5Bvalue%5D%5Byear%5D=2016
Lushoto	maize	**0.74**		
	beans	**1.40**		
	Irish potato	**0.74**		

Supplementary materials 5.2

Yield figures for the most common crops in Nyando, Rakai and Lushoto. [1]Current survey yields were reported per year and could not be attributed to a season.

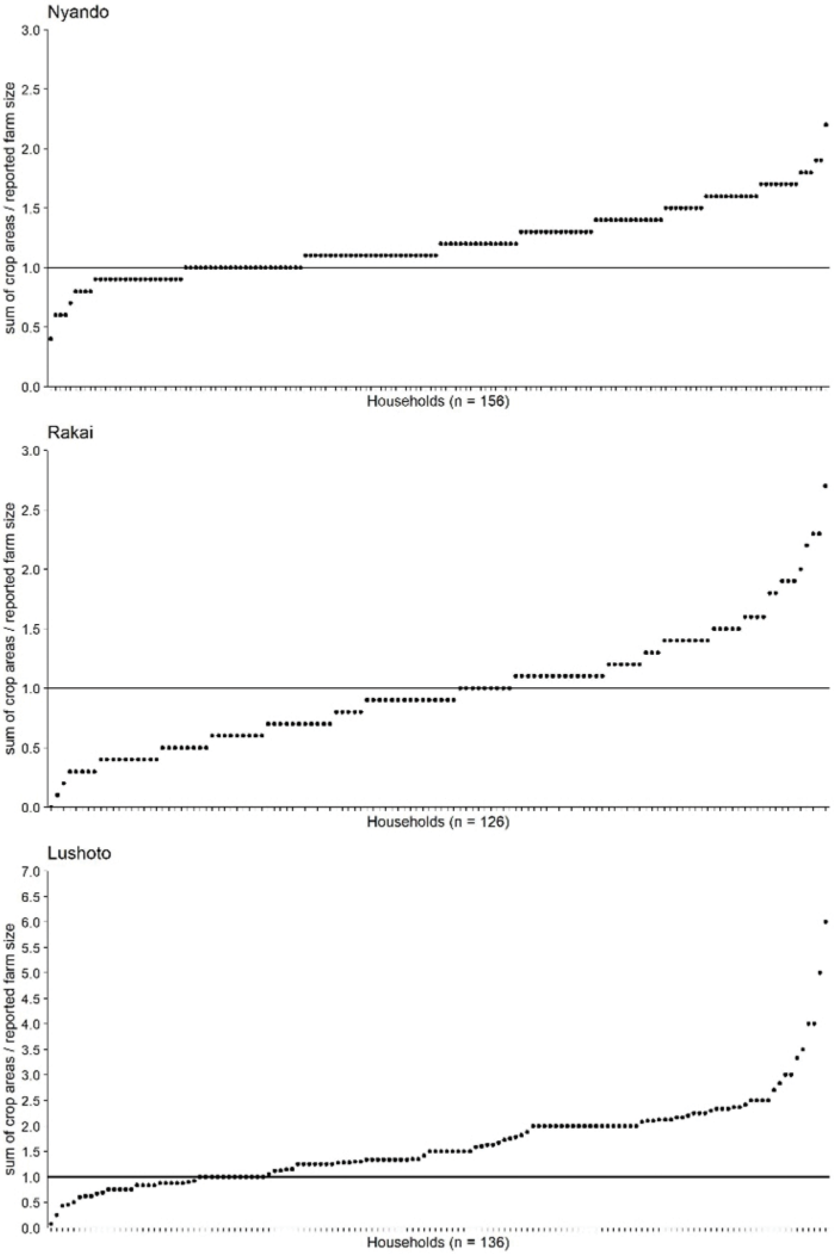
Site	crop	season	Yield figures (kg FW/ha)				
			Yw	50% Yw	Current survey	Baseline literature	Soil supply
Nyando	maize	A	11300	5650	661[1]	2000	1000
	maize	B	7458	3729		1320	660
	sugarcane	year	79200	39600	17847[1]	19000	9000
	sorghum	A	5000	2500	297[1]	700	400
	sorghum	B	3300	1650		462	264
	beans	A	2000	1000	149[1]	400	300
	beans	B	2000	1000		400	300
	kale	A	19800	9900		4900	1000
	kale	B	13100	6600		3200	700
Rakai	maize	B	6900	3450	404	1500	500
	maize	A	4140	2070	395	1000	300
	banana	year	11000	55000	5560	20000	10000
	coffee	year	6000	3000	847	600	300
	beans	A	3000	1500	411	700	300
	beans	B	2000	1000	444	400	300
	cassava	year	50000	25000	831	10000	6300
	cabbage	A	70000	35000		5000	2500

Source and reasoning for current yields	Source and reasoning water-limited yield
Yieldgap.org, Climate zone Kenya Kisii zone	Yieldgap.org, Climate zone Kenya Kisii zone
Season A times 0.66 based on relative yield in yield gap atlas for maize	Season A times 0.66 based on relative yield in yield gap atlas for maize
Francis et al., 2020	Francis et al., 2020
Yieldgap.org, Climate zone Kenya (Code=7-4-01), Embu climate zone	SC Sila: https://www.seedcogroup.com/ke/products/sorghum/sc-sila-0
Season A times 0.66 based on relative yield in yield gap atlas for maize	Season A times 0.66 based on relative yield in yield gap atlas for maize
Ojiem et al., 2014, intercropping in maize, therefore also no fertiliser application	Estimate, in intercropping with maize
Ojiem et al., 2014, intercropping in maize, therefore also no fertiliser application	Estimate, in intercropping with maize
(KEPHIS, 2018; JICA report; Mogenia, 2020)	(KEPHIS, 2018; JICA report; Mogenia, 2020)
Estimate based on long rain yields and season yield differnces of maize	Estimate based on long rain yields and season yield differnces of maize
Yieldgap, expert judgement based on Yw and the fact that most farmers grow local or improved OPV's	Yieldgap atlas Climate zone Uganda (Code=7-4-01) rainfed maize water-limited yield potential (Yw) : 6.9 tonnes / harvested ha.
Assumed based on yield gap atlas and a seasonal yield difference of 40%	Assumed based on yield gap atlas and a seasonal yield difference of 40%
Own data, unpublished; Wairegi et al., 2016: Banana coffee cropping guide	Taulya 2015, times two to account for two bunches per mat per year. In line with highest yields in banana field monitoring, own data, unpublished)
Wairegi et al., 2016: Banana coffee cropping guide	Wairegi et al., 2016: Banana-coffee system cropping guide 2015 Revised Edition
Estimate based on Nyando, pure stand	Estimate, pure stand
Estimate based on Nyando, in intercropping with maize	Estimate, in intercropping with maize
Fermont et al., 2009	Fermont et al., 2009, 50 ton in Uganda; Adiele, 2020, >90 ton but in Nigeria
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Seminis product catologue 2008

Site	crop	season	Yield figures (kg FW/ha)				
Rakai (cont.)	irish potato	B	40000	20000	1168	2700	1500
	irish potato	A	40000	20000	1261	2700	1500
	tomato	A	38400	19200	3864	7200	3000
	tomato	B	64000	32000	3864	12000	5000
Lushoto	maize	A	7200	3600	785[1]	1300	650
	maize	B	6300	3150		1130	650
	beans	A	3600	1800	354[1]	500	300
	beans	B	3600	1800		500	300
	irish potato	A	40000	20000	2780[1]	2700	1500
	cabbage	B	42000	21000	9822[1]	3000	1500
	cabbage	A	70000	35000		5000	2500

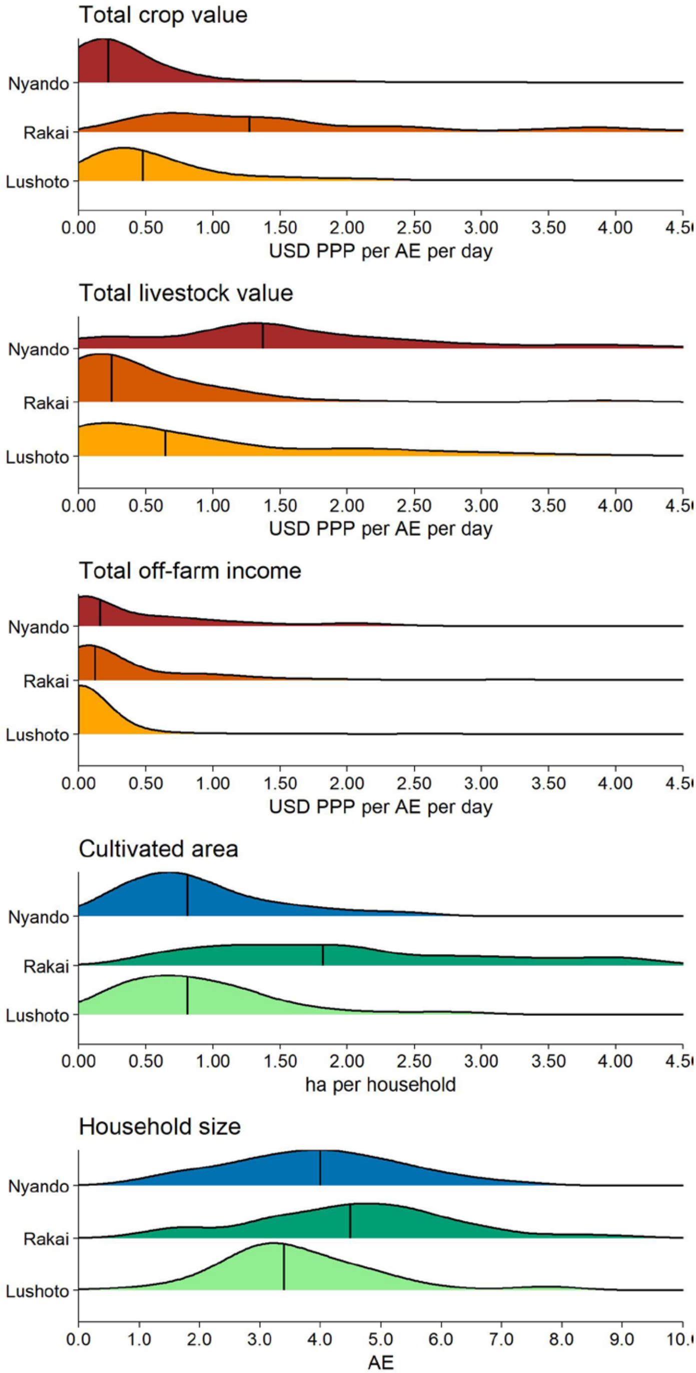
Source and reasoning for current yields	Source and reasoning water-limited yield
Gov. statistics in Harahagazwe et al., 2016	Highest yields in Harahagazwe et al., 2016
Gov. statistics in Harahagazwe et al., 2016	Highest yields in Harahagazwe et al., 2016
Everaards et al., 2011; Msogoya et al., 2016; Guijt and Reuver, 2019 and corrected for seasonal yield differences	Yield estimate Rijk Zwaan/Holland greentech; Msogoya et al., 2016 and corrected for seasonal yield differences
Everaards et al., 2011; Msogoya et al., 2016; Guijt and Reuver, 2019	Yield estimate Rijk Zwaan/Holland greentech; Msogoya et al., 2016
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	yield gap atlas, average of zone 7-5-01, 7-3-01, 7-2-01, 6-5-01, 7-4-01, 6-4-01
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	yield gap atlas season A, using yield difference in current yields
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Estimate, in intercropping with maize
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Estimate, in intercropping with maize
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Highest yields in Harahagazwe et al., 2016
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Seminis product catologue 2008
MoALF, 2016, 2014/15 Annual Agricultural Sample Survey report	Seminis product catologue 2008

Supplementary materials 5.3



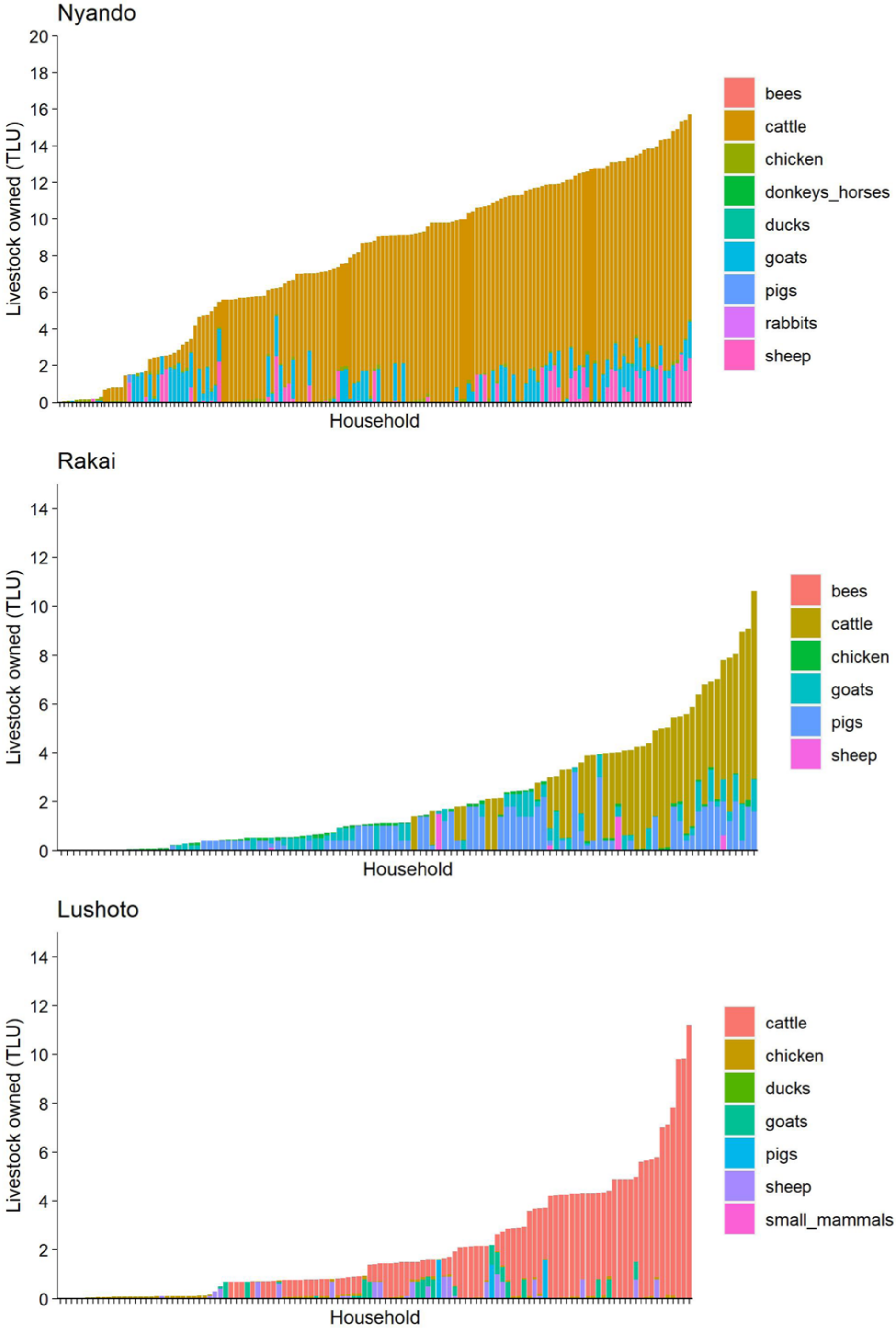
The sum of crop areas divided by the reported cultivated area for all households in the survey This fraction indicates whether the sum of crop areas is higher than, lower than, or equal to the total cultivated area.

Supplementary materials 5.4



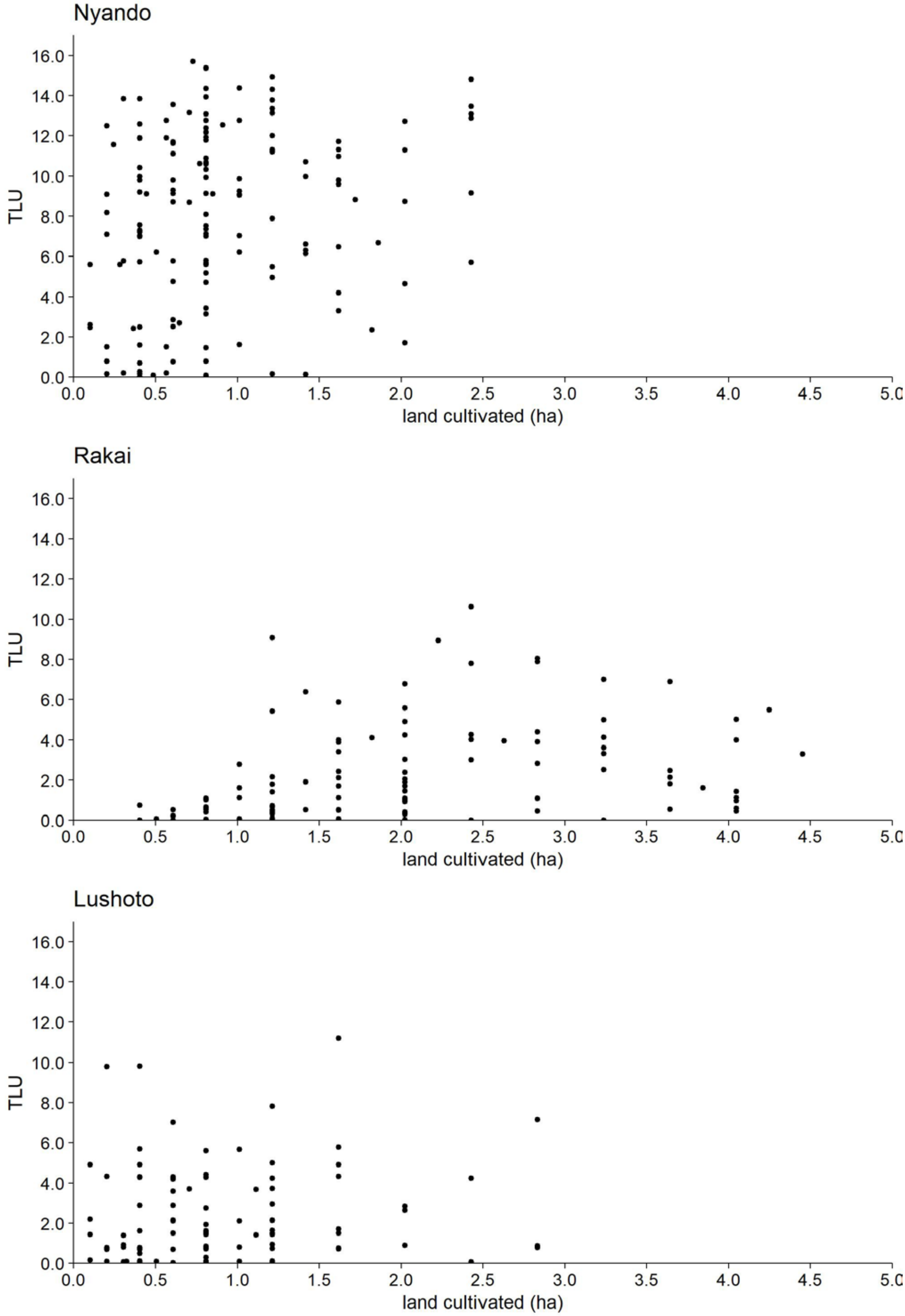
Probability density plots for total crop value produce, total livestock value produce, off-farm income, cultivated area and household size.

Supplementary materials 5.5



The distribution of livestock owned in Tropical Livestock Units (TLUs) per livestock type in each region.

Supplementary materials 5.6



Current livestock holding in relation to cultivated area per household.

Supplementary materials 5.7

The input variables used to calculate how the different crops in a farm contribute to a living income in *B1: baseline yields*-scenario.

Region	Living Income (US$ PPP/AE/day)	Sustainable farm size (ha)	Household size (AE)	Crop	Price (US$ PPP/kg)	Proportion of cultivated area (-)	Season	Yield (kg/ha)	Value produce (US$ PPP/ha)	Crop area (ha)	Production (kg)	Crop value (US$PPP/AE/day)	Crop value (% total income crop)
Nyando	4.54	2.52	4.0	maize	0.71	0.70[1]	A	2000	1412	1.77	3549	1.74	38
				maize	0.71	0.70[1]	B	1320	932	1.77	2342	1.15	25
				beans	1.25	0.70[1]	A	400	500	1.77	710	0.62	14
				beans	1.25	0.70[1]	B	400	500	1.77	710	0.62	14
				sorghum	0.57	0.21	A	700	396	0.53	374	0.15	3
				sorghum	0.57	0.21	B	462	261	0.53	247	0.10	2
				sugarcane	0.06	0.08	year	19000	1229	0.21	4010	0.18	4
Rakai	3.82	2.07	4.4	maize	0.80	0.23[1]	B	1500	1207	0.47	700	0.35	9
				beans	2.01	0.22	A	700	1408	0.46	320	0.40	10
				beans	2.01	0.23[1]	B	400	805	0.47	187	0.23	6
				irish potato	0.80	0.10	A	2700	2172	0.21	577	0.29	8
				irish potato	0.80	0.10	B	2700	2172	0.20	549	0.28	7
				banana	0.16	0.30	year	20000	3218	0.62	12469	1.25	33
				cassava	0.39	0.15	year	10000	3862	0.31	3067	0.74	19
				coffee	1.61	0.23	year	600	965	0.47	284	0.28	7
Lushoto	4.04	1.58	3.3	maize	0.74	0.90[1]	A	1300	960	1.43	1858	1.14	28
				maize	0.74	0.90[1]	B	1130	835	1.43	1615	0.99	25
				beans	1.40	0.90[1]	A	500	700	1.43	715	0.83	21
				beans	1.40	0.90[1]	B	500	700	1.43	715	0.83	21
				irish potato	0.74	0.10	A	2700	1994	0.15	408	0.25	6

Summary

The UN Sustainable Development Goals of *Zero poverty* and *Zero hunger* include *leaving no one behind* as a key principle. However, many smallholder farmers in sub-Saharan Africa (SSA) are caught in a poverty trap, a vicious cycle of low productivity and limited ability to invest. Moreover, small farm areas may limit the potential benefits that can be accrued at farm level, even if productivity would increase. Sustainable intensification is a key strategy to increase agricultural production for the growing population in SSA, while at the same time avoiding the extension of agricultural land in natural areas. In this thesis I used two perspectives. In Chapters 2 to 4 of the thesis I used an 'impact-oriented' perspective to assess, within current farming systems, to what extent integrated co-learning leads to sustainable intensification. In Chapter 5 I used a 'target-oriented' perspective to explore 'viable farm sizes' required to attain a living income (the income required for a decent living including a nutritious diet, clothes, schooling and housing). By situating this study in the East African highlands, characterized by high population density and small farm sizes, I revealed possible pathways towards more sustainable farming systems in SSA.

The use of options for sustainable intensification by smallholder farmers is often limited by knowledge and resource constraints. To address both constraints, we developed and tested an 'integrated co-learning approach' to improve farm level productivity in Chapter 2. The approach was tested by differentiating a group of co-learning farmers and a group of comparison farmers in two locations in western Kenya during five seasons. The two locations, Vihiga and Busia, differed in terms of population density. Both groups received a US$ 100 input voucher each growing season and the co-learning group also took part in co-learning activities. The integrated co-learning approach was comprised of four complementary elements: input vouchers, an iterative learning process, common grounds for communication, and complementary knowledge. Central to the approach were co-learning workshops before each season. Workshop topics built on topics from previous seasons and on farmers' feedback and researchers' observations. Activities during each season included farm management monitoring, yield measurements and evaluation interviews. This resulted in multiple learning loops for both farmers and researchers. The voucher fostered learning through increased and diversified input use. For instance, intercropped legumes were smothered by the prolific growth of maize resulting from increased fertilizer use. After setting up joint demonstrations, farmers started to use alternative spacing options for intercropping. Building common ground on concepts and processes governing farm system functioning fostered a deeper understanding by farmers on the suitability of options to their farm and by researchers on locally relevant content. Soil fertility gradients was such a concept through which judicious use of fertilizers was discussed. After five seasons, co-learning farmers had a more diverse and cohesive knowledge of their farm than comparison farmers. Co-learning farmers highlighted farm level management options, management of the parasitic weed striga and options for integrated soil fertility management as the most important things they learned. A tangible learning outcome was the continued increase in groundnut and soybean area among co-learning farm-

ers, which led to more diversified maize cropping systems. We attribute these differences to the co-learning process. Our results demonstrate how the integrated co-learning approach changed both knowledge and practices of participating farmers and researchers. The amplifying effects of the four key elements appeared to be important for enabling sustainable intensification of smallholder farming systems.

In Chapter 3 we used the detailed farm level data collected as part of the integrated co-learning approach and focussed on the impact of providing the US$ 100 input voucher each season, for five seasons in a row, on maize yields and overall farm level production in terms of value of produce. We analysed this for the two contrasting locations of the study. We compared the value of farmers' produce with the poverty line and the living income threshold. Crop yields were mainly limited by cash constraints and not technological constraints as maize yield immediately increased from 16% to 40-50% of the water-limited yield with the provision of the voucher. In Vihiga, at best, one-third of the participating households reached the poverty line. In Busia half of the households reached the poverty line and one-third obtained a living income. This difference between locations was caused by larger farm areas in Busia. Although one-third of the households increased the area farmed, mostly by renting land, this was not enough for them to obtain a living income. These results provide empirical evidence of how a current smallholder farming system could improve its productivity and value of produce upon the introduction of an input voucher. We conclude in this chapter that increasing crop yields of currently most common crops cannot provide a living income for all households with current farm sizes.

In Chapter 4 we used the detailed farm level data collected as part of the integrated co-learning approach to assess to what extend it had led to desired pathways of sustainable intensification, e.g. extensification instead of intensification and specialization instead of diversification. Our overarching aim was therefore to improve the understanding of farmer responses to input subsidies and co-learning, in order to better support future sustainable intensification pathways in smallholder farming. We used a diverse set of indicators to analyse the five seasons of detailed farm level data, which was gathered as part of a co-learning programme in western Kenya and differentiated for the comparison group and co-learning group. The integrated co-learning approach proved key in facilitating more complex changes in farm management, e.g. diversification through an increase in legume area. Other responses were mainly a result of the input voucher itself. Both groups increased maize yields (intensification) and most households became maize self-sufficient. An increase in farm and maize areas in combination with relatively low N application rates (risk of soil N mining) however, also pointed at extensification. Value of produce remained below a living income for most households due to the small farm areas. Our results highlight the difficulty of enabling an increase in yields and agricultural production, while also meeting other environmental and economic principles. The diversity of farmer responses and constraints beyond the farm level also underlined the importance of wider socio-economic developments in addition to support of sustainable intensification at farm level.

Building on the finding that farm size strongly limited farmer income, in the target-oriented perspective of Chapter 5, we explored what is a 'viable farm size', i.e. the farm area that is required to attain a 'living income'. We used survey data from three contrasting sites in the East African highlands—Nyando (Kenya), Rakai (Uganda) and Lushoto (Tanzania) to explore viable farm sizes in six scenarios. Starting from the baseline cropping system, we built scenarios by incrementally including intensified and re-configured cropping systems, income from livestock and off-farm sources. In the most conservative scenario (baseline cropping patterns and yields, minus basic input costs), viable farm areas were 3.6, 2.4 and 2.1 ha, for Nyando, Rakai and Lushoto respectively—while current median farm areas were just 0.8, 1.8 and 0.8 ha. Given the uneven distribution of current farm areas, only few of the households in the study sites (0%, 27% and 4% for Nyando, Rakai and Lushoto respectively) were able to attain a living income. Intensification of production from baseline yields to 50% of the water-limited yields strongly decreased the viable farm size, and thereby enabled 92% of the households in Rakai and 70% of the households in Lushoto to attain a living income with their current farm area. For Nyando however, intensification of crop production alone was not enough, but including income from livestock enabled the majority of households (73%) to attain a living income on their current farm areas. Our scenarios showed that increasing farm area and/or intensifying production is required for smallholder farmers to attain a living income from farming. However, such changes require considerable capital and labour investment, and possibly land reforms. Hence, smallholders would require support (e.g. input subsidies), protection (e.g. secure land access, price protection) and alternative off-farm employment options. Integrated policy is therefore imperative for all to attain a decent living.

Comparing the outcomes of the two different perspectives indicates that increasing yields of staple crops, e.g. through input subsidies, is not enough for all farmers to make a living income from current farm sizes. Larger changes are required, both within the farming system, e.g. increasing farm areas and/or cultivating more profitable crops, as well as outside the farming system, e.g. alternative employment options outside agriculture. The difficulty of enabling yield increases while also meeting other environmental and economic principles points at the need to prioritise specific indicators, e.g. yield increase, maize self-sufficiency, income and N-use efficiency, over others when improving current smallholder farming systems. The integrated co-learning approach can be deployed to explore incentives for smallholder farmers to sustainably intensify. Further research is required on how to scale the approach and integrate it into extension systems while keeping the valuable farmer-researcher feedback. The viable farm size as a benchmark is a useful method for assessing how to *leave no one behind* while moving towards more sustainable farming systems.

Samenvatting

De duurzame ontwikkelingsdoelen van de VN hebben *Geen armoede* en *Geen honger* hebben *Niemand achter laten blijven* als belangrijk onderliggend principe. Veel kleinschalige boeren in Afrika ten zuiden van de Sahara zitten echter vast in armoede door een vicieuze cirkel van lage productiviteit en beperkte mogelijkheden om te investeren. Daarnaast zorgt de kleinschaligheid van het areaal per boerderij de verdere verbetering van de verdiensten beperken, zelfs als opbrengsten omhoog zouden gaan. Duurzame intensifiëring wordt gezien als een belangrijke strategie om productie van landbouw te verhogen voor de groeiende bevolking in Afrika ten zuiden van de Sahara, met als voordeel dat productie verhoging niet hoeft te leiden tot uitbreiding van landbouw gebied naar plekken die nu nog natuur zijn. In deze thesis heb ik twee perspectieven gebruikt In Hoofdstukken 2 tot 4 van dit proefschrift heb ik een 'impact-georiënteerd' perspectief gebruikt om te onderzoeken hoe in huidige landbouwsystemen, een 'geïntegreerde gezamenlijk leren-aanpak' kan leiden tot duurzame intensifiëring. In Hoofdstuk 5 heb ik een 'doelgericht' perspectief gebruikt om te na te gaan wat een 'rendabel bedrijfsgrote' is voor het verkrijgen van een 'living income' (het inkomen dat nodig is om een behoorlijk bestaan te hebben, inclusief geld voor een voedzaam dieet, kleding, schoolgeld en huisvesting). Door het dit onderzoek plaats te laten vinden in de Oost-Afrikaanse hooglanden, die gekenmerkt worden door een hoge bevolkingsdichtheid en kleine boeren bedrijfjes, geeft dit het inzicht in mogelijke wegen richting duurzaam geïntensifieerde landbouw systemen in Afrika ten zuiden van de Sahara.

Het gebruik van mogelijkheden voor duurzame intensifiëring door kleinschalige boeren word vaak beperkt door beperkte kennis en beperkte middelen. Om dit beide te ondervangen hebben we in Hoofdstuk 2 een 'geïntegreerde gezamenlijk leren-aanpak' ontwikkeld en getest, met als doel om productiviteit op boerderijniveau te verbeteren. De aanpak is getest door met twee groepen boeren te werken, een gezamenlijk leren groep en een vergelijkingsgroep in twee locaties in west Kenia, gedurende vijf seizoenen. De twee locaties, Vihiga en Busia, verschilden qua bevolkingsdichtheid. Beide groepen ontvingen een waardebon van 100 Amerikaanse dollar (US$) per seizoen voor landbouwbenodigdheden, waarbij de gezamenlijk leren groep ook deelnam aan activiteiten voor gezamenlijk leren. De geïntegreerde gezamenlijk leren-aanpak behelsde vier complementaire onderdelen: waardebonnen voor landbouw benodigdheden, een iteratief leerproces, een gemeenschappelijke basis voor communicatie en complementaire kennis. Centraal onderdeel van de aanpak was een gezamenlijk leren workshop die plaats vond voor het begin van elk teeltseizoen. Onderwerken voor de workshop bouwden ieder seizoen voort op onderwerpen van het voorgaande seizoen, terugkoppeling van boeren en observaties van de onderzoekers gedurende het seizoen. Activiteiten gedurende het seizoen behelsden het monitoren van bedrijfsmanagement, het meten van opbrengst en evaluatie interviews aan het einde van het seizoen. Dit resulteerde in meerdere leer cycli, zowel voor boeren als voor onderzoekers. De waardebon bevorderde het leren door het gebruik van meer en meer diverse landbouw benodigdheden. Bijvoorbeeld, de peulgewassen, die in mengteelt met mais werden verbouwd, werden verstikt door de nu veel beter groeide mais door het toegenomen gebruik van kunstmest. Na het gezamenlijk opzetten van demonstratievelden begonnen boeren met het gebruiken van verbeterde plant afstanden voor meer intensieve mengteelten. Het ontwikkelen van een gezamenlijke basis voor communicatie over onderliggende concepten en processen van landbouwsystemen zorgde voor een beter begrip van boeren over passende opties voor hun bedrijf. Bij de onderzoekers zorgde het voor een beter begrip van wat lokaal relevante opties waren. Bodemvruchtbaarheidsgradiënten waren zo'n gezamenlijk basis voor communicatie, onder andere voor het bespreken van verstandig kunstmest gebruik. Na vijf seizoenen hadden de boeren die deelnamen aan het gezamenlijk leren een meer divers en samenhangend begrip van hun bedrijf dan de boeren uit de vergelijkingsgroep. De boeren uit de gezamenlijk leren groep benadrukten onder andere management op boerderijniveau, bestrijding van het parasitaire onkruid striga en opties voor geïntegreerd bodembeheer, als de belangrijkste dingen die ze hadden geleerd. Een andere tastbare resultaat was het steeds groter wordende areaal met pinda en sojabonen bij de gezamenlijk leren boeren. Wij kennen deze verschillen toe aan het gezamenlijk leren proces. Onze resultaten laten zien dat de geïntegreerde gezamenlijk leren-aanpak zorgde voor een verandering in zowel kennis en uitvoering in de praktijk, van boeren en onderzoekers. Het versterkende effect van de vier complementaire onderdelen bleek belangrijk te zijn voor het bevorderen van duurzame intensifiëring van kleinschalige landbouwsystemen.

In Hoofdstuk 3 maakten we gebruik van de gedetailleerde data die was verzameld als onderdeel van de geïntegreerde gezamenlijk leren aanpak. Het hoofdstuk focust op het effect van het beschikbaar stellen van de US$ 100 waardebon voor landbouwbenodigdheden per seizoen gedurende vijf seizoenen, op maïs opbrengsten en op totale opbrengsten op boerderijniveau. De totale opbrengsten op boerderijniveau zijn uitgedrukt in de economische waarde van de productie. We hebben dit geanalyseerd voor de twee contrasterende studielocaties. Daarnaast hebben we de waarde van de productie vergeleken met de armoedegrens en het living income als referentiewaarden. Gewasopbrengsten werden voornamelijk beperkt door geld tekort en niet door technische beperkingen, aangezien maisopbrengsten direct omhoog gingen van 16% naar 40-50% van de water-gelimiteerde potentiële opbrengst, toen boeren gebruik konden maken van de waardebon. In Vihiga behaalden echter hooguit één-derde van de deelnemende boeren de armoedegrens. In Busia haalde de helft van de boeren de armoedegrens en één-derde verkreeg een living income. Het verschil tussen de locatie kwam voornamelijk door het grotere areaal dat de boeren in Busia hebben. En alhoewel één-derde van de boeren hun areaal vergroten, meesten door land te huren, dit zorgde niet voor een groot genoeg verschil om een living income te verkrijgen. Deze resultaten geven empirisch bewijs voor hoe de productiviteit en de economische waarde van de totale productie per bedrijf kan toenemen in een bestaand landbouwsysteem van kleinschalige boeren als een waardebon voor landbouwbenodigdheden wordt verstrekt. Wij concluderen in dit hoofdstuk dat het verhogen van gewasopbrengsten van de momenteel belangrijkste gewassen er niet voor kan zorgen dat alle boeren kunnen worden voorzien in een living income, met hun huidige bedrijfsgroottes.

In Hoofdstuk 4 gebruikten we weer dezelfde gedetailleerde data die was verzameld als onderdeel van de geïntegreerde gezamenlijk leren aanpak. Dit keer om vast te stellen in hoeverre de aanpak leidde tot de gewenste wegen richting duurzame intensifiëring, bijvoorbeeld intensifiëring in plaats van extensifiëring en diversifiëring in plaats van specialisatie. Ons achterliggende doel was om beter inzicht te krijgen in wat boeren doen als ze worden gesubsidieerd en deelnemen aan gezamenlijk leren, om daarmee in het vervolg de gewenste wegen richting duurzame intensifiëring beter te kunnen bevorderen in kleinschalige landbouw. We gebruikten een diverse set van indicatoren om de getailleerde data op boerderijniveau te analyseren, die we hadden verzameld tijdens het gezamenlijk leren project. We maakten daarbij onderscheid tussen de vergelijkingsgroep en de gezamenlijk leren groep. De geïntegreerde gezamenlijk leren-aanpak bleek essentieel te zijn voor het faciliteren van de meer complexe verandering in bedrijfsvoering, bijvoorbeeld diversificatie doormiddel van een groter areaal met peulvruchten. Andere uitkomsten waren voornamelijk een resultaat van het verstrekken van de waardebon voor landbouwbenodigdheden. Beide groepen verhoogden hun maïsopbrengsten (intensifiëring) en de meeste huishoudens werden zelfvoorzienend in maïs. Een toename in areaal per boerenbedrijf en in maïs areaal in combinatie met relatief lage stikstof bemesting (risico op het stikstof uitmijnen van de bodem) wees echter ook in de richting van extensifiëring. De economische waarde van de productie bleef onder het living income voor de meeste huishoudens door hun kleine landbouw areaal. Deze resultaten laten zien hoe moeilijk het is om zowel opbrengst verhoging en totale productie te bevorderen, alsmede de milieu en economische principes na te streven. De diversiteit in wat boeren deden en de beperkingen die buiten het boerderijniveau liggen benadrukten ook het belang van grotere sociaaleconomische ontwikkelingen naast het bevorderen van duurzaam intensifiëring op boerderijsniveau.

Voortbouwend op de uitkomst dat de grote van het landbouwareaal per boerenbedrijf een sterk beperkend effect had op het inkomen van boeren, verkenden we doormiddel van een doelgericht perspectief in Hoofdstuk 5 wat een rendabel bedrijfsgrootte is, dat wil zeggen, het landbouwareaal dat nodig is om een living income te verkrijgen. We maken hierbij gebruik van data uit enquêtes uit drie contrasterende gebieden in de Oost Afrikaanse hooglanden—Nyando (Kenya), Rakai (Uganda) en Lushoto (Tanzania) – en verkenden daarmee zes scenario's. Het eerste scenario bevatte een basis teeltsysteem en bijbehorende opbrengsten. De daar op volgende scenario's bouwden daar per scenario op voort met steeds verder intensifiëring en opnieuw geconfigureerde teeltsystemen, en daar aan toegevoegd het inkomen van vee en van buiten het bedrijf. De rendabele bedrijfsgrootte in het meest conservatieve scenario (basis teeltsysteem en opbrengsten, minus kosten voor landbouwbenodigdheden) waren 3.6, 2.4 and 2.1 ha, in Nyando, Rakai and Lushoto respectievelijk – terwijl de mediaan van de huidige bedrijfsgroottes 0.8, 1.8 en 0.8 ha was. Doordat er een ongelijke verdeling in huidige bedrijfsgroottes was, verkregen er momenteel maar een paar huishoudens een living income (0%, 27% en 4% in Nyando, Rakai and Lushoto respectievelijk). Intensifiëring van de opbrengsten, van het basisniveau naar 50% van de water-gelimiteerde opbrengst, zorgde voor een sterke verkleining van de rendabele bedrijfsgrootte, met als resultaat dat 92% van de huishoudens in Rakai en 70% van de huishoudens in Lushoto een living income konden verkrijgen met hun huidige bedrijfsgrootte. Intensifiëring van alleen de gewasproductie was in Nyando niet voldoende. Het toevoegen van het inkomen uit vee zorgde er echter voor dat het grootste deel van de boeren (73%) een living income konden verkrijgen. Onze scenario uitkomsten lieten daarmee zien dan een vergrote bedrijfsgrootte en/of de intensifiëring van de productie nodig is voor kleinschalige boeren om een living income te verkrijgen uit landbouw. Echter, zulke veranderingen vereisen aanzienlijke kapitaal en arbeidsinvesteringen en mogelijk landhervormingen. Kleinschalige boeren behoeven dus ondersteuning (bijvoorbeeld subsidie voor landbouwbenodigdheden), bescherming (bijvoorbeeld goede landrechten en prijsbescherming) en nieuwe banen buiten de landbouw. Geïntegreerd beleid is daarom onomstotelijk voor het verkrijgen van een redelijk bestaan voor kleinschalige boeren.

De uitkomsten van de twee verschillende perspectieven laten zien dat het verhogen van opbrengsten van basisgewassen, bijvoorbeeld door het verschaffen van subsidies voor landbouwbenodigdheden, niet genoeg is voor alle boeren om een living income te verkrijgen met hun huidige bedrijfsgroottes. Grotere verandering zijn daarom nodig, zowel in het landbouwsysteem, bijvoorbeeld het vergroten van bedrijfsgroottes en/of het telen van gewassen met een betere economische opbrengst, alsmede veranderingen buiten de landbouw, bijvoorbeeld het creëren van banen in de industrie. De moeilijkheid om zowel opbrengst te verhoging te behalen, alsmede de milieutechnische en economische principes na te streven, laat zien dat het nodig is om specifieke indicatoren te prioriteren, bijvoorbeeld het verhogen van opbrengsten, maïs zelfvoorziening, inkomen en stikstof gebruiksefficiëntie, ten opzichte van andere indicatoren, als het doel is kleinschalige landbouwsystemen te verbeteren. De geïntegreerde gezamenlijk leren-aanpak kan als methode verder worden ingezet om mogelijke nieuwe stimulansen te onderzoeken die kunnen worden gebruikt om duurzame intensifiëring te bevorderen bij kleinschalige boeren. Verder onderzoek is nodig om inzicht te krijgen in hoe de aanpak op grote schaal kan worden toegepast en hoe deze kan worden geïntegreerd in bestaande landbouwvoorlichting. Het is belangrijk dat er daarbij naar wordt gekeken hoe de belangrijke aspecten van de aanpak kunnen worden behouden, zoals de nuttige uitwisseling tussen boeren en onderzoekers. De rendabele bedrijfsgrootte als referentiewaarde kan daarnaast worden gebruikt voor verder onderzoek naar hoe n*iemand achter te laten* op de weg naar duurzamere landbouwsystemen.

Gearfetting

De doelen foar duorsume ûntwikkeling van de Feriene Naasjes befetsje; *gjin earmoed*, *gjin honger* ha *nimmen efterlite* as in wichtich ûnderlizzend prinsipe. In protte lytsskalige boeren yn Afrika besuden de Sahara sitte lykwols fêst yn earmoede troch in vicieuze sirkel fan lege produktsje en beheinde mooglikheden om te ynvestearjen. Dêrnjonken beheint de lytse omfang fan it oantal bunders per boere bedriuw de mooglikheden foar bettere ynkomsten, sels as de opbringsten omheech geane. Duorsume yntinsivearring wurdt sjoen as in wichtige strategy om de agraryske produksje te fergrutsjen foar de groeiende befolking yn Afrika besuden de Sahara, mei as foardiel dat tanimmende produksje net hoecht te lieden ta útwreiding fan de lânbougrûn yn gebieten dy't no noch natuer binne. Yn dit proefskrift haw ik twa perspektiven brûkt. Yn Haadstikken 2 oant 4 fan dit proefskrift haw ik in ynfloedrjochte perspektyf brûkt om te ûndersykjen hoe't yn hjoeddeiske lânbousystemen, in yntegreare gearwurkjende learbenadering liede kin ta duorsume yntinsivearring. Yn haadstik 5 brûkte ik in 'doelrjochte' perspektyf om te beskôgjen wat in 'rendabele bedriuwsgrutte' is foar it krijen fan in 'living income' (it ynkommen dat nedich is om in fatsoenlik libben te hawwen, ynklusyf jild foar in voedzaam dieet, klean, skoaljild en húsfesting). Troch dat dit ûndersyk barde yn de East-Afrikaanske heechlannen, dy't karakterisearre wurde troch in hege befolkingstichtens en lytse lânbouwbedriuwen, jout dit ûndersyk ynsjoch yn mooglike paden nei takomstige duorsume en yntensivearre lânbousystemen yn Afrika besuden de Sahara.

It brûken fan mooglikheden foar duorsume yntinsivearring troch lytsskalige boeren wurdt faak beheind troch beheinde kennis en beheinde middels. Om beide te oerwinnen, hawwe wy yn Haadstik 2 in 'yntegreare gearwurkjende learoanpak' ûntwikkele en test mei as doel de produktiviteit op buorkerijnivo te ferbetterjen. De oanpak is hifke troch te wurkjen mei twa groepen boeren, in gearwurkjende leargroep en in fergelikingsgroep op twa lokaasjes yn westlik Kenia, oer fiif seizoenen. De twa lokaasjes, Vihiga en Busia, ferskille yn befolkingstichtens. Beide groepen krigen in weardebon fan 100 Amerkaanske dollar (US$) per seizoen foar lânboubenodigdheden, wêrby de gearwurkjende leargroep ek mei die oan gearwurkjende learaktiviteiten. De yntegreare oanpak fan gearwurkjend learen befette fjouwer komplementêre komponinten: in weardebon foar lânboubenodigdheden, in werheljend learproses, in mienskiplike basis foar kommunikaasje en komplemintêre kennis. Sintraal yn die oanpak stie in gearwurkjende learworkshop dy't plak fûn foar it begjin fan alle groeiseizoenen. Ûnderwerpen foar workshops bouden els seizoen fjirder op ûnderwerpen út it foarige seizoen, weromkoppeling fan boeren en observaasjes fan de ûndersikers yn it hiele seizoen. Aktiviteiten yn it seizoen omfetten it byhâlden fan wat de boeren dienen op harren buorkerij, it mjitten fan opbringst en evaluaasjepetearen. Dat resultearre yn meardere learsyklusen, sawol foar boeren as foar ûndersikers. De weardebon befoardere it learen troch it brûken fan mear en in grutter ferskaat oan lânboubenodigdheden. Sa smoarden de pûlgewaaksen, dy't yn minggewaaksen mei mais ferboud waarden, yn de no folle better groeiende mais troch it brûken fan mear keunstdong. Nei it opsetten fan demonstraasjefjilden yn de mande mei de boeren, begongen de boeren ferbettere plantôfstannen te brûken foar dizze yntensive mingteelt. It ûntwikkeljen fan in mienskiplike grûn foar kommunikaasje oer ûnderlizzende konsepten en prosessen fan lânbousystemen ferbettere it begryp fan boeren foar passende opsjes foar har bedriuw. Derneist joech it de ûndersikers in better begryp fan wat lokaal relevante opsjes wiene. Grûn fruchtberensgradiënten wiene sa'n mienskiplike basis foar kommunikaasje, bygelyks foar it besprekken fan ferstannich keunstdonggebrûk. Nei fiif seizoenen hienen de boeren dy't meidienen oan it gearwurkjende learen in ferskaat en gearhingjender begryp fan harren boerebedriuw as de boeren yn de fergelikingsgroep. De mienskiplike learende boeren beklammen it belang fan management op it boerebedriuw, bestriding fan it parasitaire ûnkrûd striga en yntegreare opsjes foar boaiembehear as de wichtichste dingen dy't se leard hiene. In oar taastber resultaat wie it tanimmende areaal mei apenúten en sojabeanen by de mienskiplik learende boeren. Wy skriuwe dizze ferskillen ta oan it mienskiplike learproses. Us resultaten litte sjen dat de yntegreare gearwurkjende learoanpak in feroaring yn sawol kennis as ymplemintaasje yn de praktyk fan boeren en ûndersikers bringt. It fersterkjend effekt fan de fjouwer komplementêre komponinten wie wichtich foar it befoarderjen fan duorsume yntinsivearring fan lytsskalige lânbousystemen.

Yn Haadstik 3 brûkten wy de detaillearre gegevens sammele as ûnderdiel fan 'e yntegreare gearwurkjende learen oanpak. It haadstik rjochtet him op it effekt fan it beskikber stellen fan de US$ 100 weardebon per seizoen foar lânboubenodigdheden foar fiif seizoenen, op mais-opbringsten en op totale opbringsten op buorkerijnivo, útdrukt yn 'e ekonomyske wearde fan produksje. Wy analysearren dit foar de twa kontrastearjende stúdzje plakken. Dêrnjonken hawwe wy de wearde fan produksje fergelike mei de earmoedegrins en it living income as referinsjewearden. De opbringsten fan gewaaksen waarden yn it foarste plak beheind troch jildtekoarten en net troch technyske beheiningen, om't de maisopbringsten fuortendaliks omheech gong fan 16% nei 40-50% fan 'e wetterbeheinde potinsjele opbringst, doe't boeren de weardebon brûke koene. Yn Vihiga berikte lykwols net mear as in tredde fan de dielnimmende boeren de earmoedegrins. Yn Busia berikte de helte fan de boeren de earmoedegrins en krige in tredde part in living income. It ferskil tusken de lokaasje kaam benammen troch it gruttere lânbouoervlak dat de boeren yn Busia hawwe. En hoewol in tredde part fan de boeren har lânbouoervlak fergrutte tydens it projekt, de measten troch it hieren fan lân, makke dat net in grut genôch ferskil om in living income te generearjen. Dizze resultaten jouwe empirysk bewiis foar hoe't produktiviteit en ekonomyske wearde fan 'e totale produksje per boerebedriuw tanimme kin yn in besteande boeresysteem as in weardebon foar lânboubenodigdheden jûn wurdt oan lytsskalige boeren. Wy konkludearje yn dit haadstik dat it tanimmen fan gewaaksopbringsten fan de op dit stuit wichtichste gewaaksen der net foar soargje kinne dat alle boeren, mei harren hjoeddeiske areaalgrutte, fan in living income foarsjoen wurde kinne.

Yn haadstik 4 brûkten wy wer deselde detaillearre gegevens sammele as ûnderdiel fan 'e yntegreare gearwurkjende learen oanpak. Dit kear om fêst te stellen yn hoefier't de oanpak late ta de winske paden nei duorsume yntinsivearring, bygelyks yntinsivearring ynstee fan ekstensivearring en diversifikaasje ynstee fan spesjalisaasje. Us ûnderlizzende doel wie om in better begryp te krijen fan wat boeren dogge as se subsydzje krije en meidogge oan gearwurkjend tearen, om dermei yn de takomst de winske paden nei duorsume yntinsivearring yn de lytsskalige lânbou better befoarderje te kinnen. Wy brûkten in ferskaat oan yndikatoaren om de detaillearre gegevens op buorkerijnivo te analysearjen. Wy makken in ûnderskied tusken de fergelikingsgroep en de gearwurkjende leargroep. De yntegreare oanpak fan gearwurkjend learen blykte essensjeel te wêzen foar it fasilitearjen fan de mear komplekse feroaring yn bedriuwsfiering, bygelyks diversifikaasje troch in grutter areaal mei pûlgewaaksen. Oare útkomsten wiene benammen in gefolch fan it útjaan fan de waerdebonnen. Beide groepen fergrutten harren maisopbringsten (yntinsivearring) en de measte húshâldings wiene selsfoarsjennend mei mais. Dochs wiisde in ferheging fan it areaal per boerenbedriuw en fan it maisareaal yn kombinaasje mei in relatyf lege stikstofjefte (risiko op boaiemútputting fan stikstof) yn de rjochting fan ekstensivearring. De ekonomyske wearde fan de produksje bleau foar de measte húshâldings ûnder it living income, troch harren lytse lânbouoervlak. Dizze resultaten litte dus sjen hoe dreech it is om sawol de opbringstferhegingen as de totale produksje te befoarderjen, en ek de miljeu- en ekonomyske prinsipes te realisearjen. It ferskaat yn wat boeren diene en de beheiningen bûten it buorkerijnivo ûnderstreke ek it belang fan gruttere sosjaal-ekonomyske ûntwikkelingen neist it befoarderjen fan duorsume yntinsivearring op buorkerijnivo.

Op grûn fan de fynst dat de grutte fan it lânbouoervlak per buorkerij in sterk beheinend effekt hie op it ynkommen fan boeren, hawwe wy yn it doelrjochteperspektyf fan Haadstik 5 ûndersocht wat in libbensfetbere buorkerijgrutte is, dat is it lânbouoervlak dat nedich is om in living income te krijen. Wy brûke enkêtegegevens fan trije kontrastearjende gebieten yn 'e East-Afrikaanske Heechlannen – Nyando (Kenia), Rakai (Oeganda) en Lushoto (Tanzania) – om seis senario's te ûndersykjen. It earste senario befette in basiskultivaasjesysteem en byhearrende opbringsten. Folgjende senario's bouden op foar mei hieltyd tanimmende yntinsivearring en opnij konfigurearre lânbou systemen, plus fee en ynkommen fan bûten it boerebedriuw. De libbensfetbere buorkerijgrutte yn it meast konservative senario (basiskultivaasjesysteem en basis opbringsten, minus kosten foar lânboubenodigdheden) wiene 3,6, 2,4 en 2,1 bunder, respektivelik yn Nyando, Rakai en Lushoto - wylst op it stuit de mediaan fan pleatsgrutte wiene 0,8, 1,8 en 0,8 bunder. Troch de ûngelikense ferdieling yn hjoeddeistige areaal grutte per buorkerij krije op it stuit mar in pear húshâldings in living income (0%, 27% en 4% yn respektivelik Nyando, Rakai en Lushoto). It yntinsivearjen fan produksje fan it basisnivo nei 50% fan 'e wetterbeheinde opbringst potinsjeel fermindere de libbensfetbere buorkerijgrutte in soad, wêrtroch't 92% fan 'e húshâldings yn Rakai en 70% fan 'e húshâldings yn Lushoto in living income krije koenen mei har hjoeddeistige areaalgrutte. It yntinsivearjen fan gewaaksproduksje allinnich wie net genôch yn Nyando. It tafoegjen fan it ynkommen út fee soarge der lykwols foar dat de grutste part fan de boeren (73%) in living income krije koe. Us senario-útkomsten lieten dus sjen dat in gruttere lânbouareaal per buorkerij en/as yntinsivearring fan'e produksje nedich is foar lytsskalige boeren om in living income út de lânbou te krijen. Sokke feroarings fereaskje lykwols grutskalige kapitaal- en arbeidsynvestearring en mooglik lânherfoarming. Lytsskalige boeren hawwe derom stipe nedich (bygelyks subsydzjes foar lânboubenodigdheden), beskerming (bygelyks goede lânrjochten en priisbeskerming) en nije banen bûten de lânbou. Yntegreare belied is dêrom ûnmisber foar it krijen fan in ridlik bestean.

De útkomsten fan de twa ferskillende perspektiven litte sjen dat it fergrutsjen fan de opbringst fan basisgewaaksen, bygelyks troch it jaan fan subsydzjes foar lânboubenodigdheden, net foar alle boeren genôch is om mei harren hjoeddeiske lânbouoervlak in living income te realisearjen. Der binne dêrom gruttere feroarings nedich, sawol yn it lânbousysteem, bygelyks it fergrutsjen fan lânbouoervlak en/of it ferbouwen fan gewaaksen mei bettere ekonomyske opbringsten, en ek feroaringen bûten de lânbou, bygelyks it skeppen fan banen yn'e yndustry. De swierrichheid om sawol opbringstferheging as miljeu- en ekonomyske prinsipes te berikken lit de needsaak sjen om spesifike yndikatoaren te prioritearjen, lykas opbringstferheging, selsfoarsjennigens fan mais, ynkommen en stikstofbenutting, relatyf oan oare yndikatoaren, at lytsskalige lânbousystemen ferbettere wurde. De yntegreare oanpak fan gearwurkjend klearen kin derneist brûkt wurde om mooglike nije stimulânsen te ferkennen dy't brûkt wurde kinne om duorsume yntinsivearring ûnder lytsskalige boeren te befoarderjen. Fierder ûndersyk is nedich om te begripen hoe't de oanpak op gruttere skaal tapast wurde kin en hoe't it yntegrearre wurde kin yn de besteande lânbou foarljochtingtsjinst. It is dan wichtich op de belangryke aspekten fan 'e oanpak, lykas de nuttige útwikseling tusken boeren en ûndersikers, te behâlden. De rendabele buorkerijgrutte as referinsjewearde kin derneist brûkt wurde yn fjirder ûndersyk nei hoe as *nimmen efter te litten* der útsjocht op 'e wei nei duorsumer lânbousystemen.

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exactly (dis)agreed and which maize varieties farmers actually grow.

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About the author

Wytze Marinus was born on 21 October 1989 in the beautiful village of Nij Beets, Frisia, the Netherlands. By the age of 12 he owned over 20 goats, was breeding rabbits for pet stores and was selling eggs in the neighbourhood. Being a smallholder farmer early on, made him realize how much work it is if you have limited land and have to scavenge for roadside gras and to cut off branches to feed your animals. After completing high school (VWO) in Drachten he took a gap year, traveling through Asia, working on farms in Australia and doing volunteer work in the Palestinian Territories. He did a BSc in International Land and Water Management at Wageningen University which reminded him again of his passion for growing crops. He therefore continued doing an MSc in Plant Sciences, focusing on smallholder agriculture in sub-Saharan Africa. In his first MSc thesis he conducted a cropping experiment with cowpea-maize relay cropping in northern Ghana to access its possible benefits and conducted interviews to discuss its opportunities and constraints with farmers. In his second thesis he conducted a detailed farm characterization to access opportunities and constraints for climbing bean cultivation in the Ugandan highlands. He then continued at the Plant Production Systems groups of Wageningen University as a research assistant for one year, developing a user's manual and an education module for the NUANCES-FARMSIM model. He also conducted a sustainability assessment of smallholder farming systems in western Kenya and northern Ghana as part of the N2Africa project. This work evolved in a peer-reviewed book chapter. He then started his PhD research at the same group, doing research on working towards more sustainable farming systems in the East African highlands. He assessed this from two perspectives. The first perspective included multiple season co-learning cycles with groups of farmers in Kenya and Uganda to explore current opportunities for sustainable intensification and the impacts of using these for participating farmers. The second perspective was a scenario analysis, based on survey data, to assess what is a 'viable farm size' for smallholder farmers, using the living income as a benchmark. Following his PhD, he plans to continue doing research that aims at improving smallholder farmers' livelihoods: moving from the hard life of being a smallholder farmer, with limited land, limited income and strugling to get by, towards a decent living and a living income. In his free time he likes to do sports (running, rowing, cycling), read, renovate a house, grow vegetables and make furniture.

List of publications

Peer reviewed scientific publications

Almekinders, C., Hebinck, P., **Marinus, W.**, Kiaka, R., Waswa, W., 2021. Why farmers use so many different maize varieties in West Kenya. Outlook Agric. 50. https://doi.org/10.1177/00307270211054211

Braber, H. den, Ven, G. van de, Ronner, E., **Marinus, W.**, Languillaume, A., Ochola, D., Taulya, G., Giller, K.E., Descheemaeker, K., 2021. Manure matters: prospects for regional banana-livestock integration for sustainable intensification in South-West Uganda. https://doi.org/https://doi.org/10.1080/14735903.2021.1988478

Marinus, W., Descheemaeker, K.K.E., van de Ven, G.W.J., Waswa, W., Mukalama, J., Vanlauwe, B., Giller, K.E., 2021. "That is my farm" – An integrated co-learning approach for whole-farm sustainable intensification in smallholder farming. Agric. Syst. 188, 103041. https://doi.org/10.1016/j.agsy.2020.103041

Marinus, W., Ronner, E., van de Ven, G.W.J., Kanampiu, F., Adjei-nsiah, S., Ken, E.G., 2018. The devil is in the detail! Sustainability assessment of African smallholder farming, in: Bell, S., Morse, S. (Eds.), Sustainability Indicators and Indices. Routledge, London, pp. 453–476.

Ronner, E., Descheemaeker, K., **Marinus, W.**, Almekinders, C.J.M., Ebanyat, P., Giller, K.E., 2018. How do climbing beans fit in farming systems of the eastern highlands of Uganda? Understanding opportunities and constraints at farm level. Agric. Syst. 165, 97–110. https://doi.org/10.1016/j.agsy.2018.05.014

van de Ven, G.W.J., de Valença, A., **Marinus, W.**, de Jager, I., Descheemaeker, K.K.E., Hekman, W., Mellisse, B.T., Baijukya, F., Omari, M., Giller, K.E., 2020. Living income benchmarking of rural households in low-income countries. Food Secur. https://doi.org/10.1007/s12571-020-01099-8

Scientific reports

Marinus, W., Ronner, E., van de Ven, G.W.J., Kanampiu, F., Adjei-Nsiah, S., Giller, K.E., 2016. What role for legumes in sustainable intensification? - case studies in Western Kenya and Northern Ghana for PROIntensAfrica. 66 pp. www.N2Africa.org.

Marinus, W., van de Ven, G., Descheemaeker, K., Zijlstra, M., Koot, T., Giller, K., 2016. NUANCES-FARMSIM – Analysing smallholder crop-livestock systems in sub-Saharan Africa.

Popular media

Marinus, W., van Reemst, L.I., Kinyanjui, S.N., 2018. Waarom Keniaanse boeren wél 21ste eeuwse mais verbouwen (Why Kenyan farms dó grows 21st century maize varieties). de Volkskrant. https://www.volkskrant.nl/kijkverder/2018/voedselzaak/ideeen/waarom-keniaanse-boeren-wel-21ste-eeuwse-mais-verbouwen/

PE&RC Training and Education Statement

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

Review of literature (4.5 ECTS)
- Analysing smallholder crop livestock systems in sub-Saharan Africa

Writing of Project proposal (4.5 ECTS)
- Towards sustainable farming in the east African Highlands

Post-graduate courses (4.8 ECTS)
- Farming systems and rural Livelihoods, Uganda; PE&RC (2018)
- Linear models; PE&RC (2019)
- Mixed linear models; PE&RC (2019)
- Generalized linear models; PE&RC (2019)

Deficiency, refresh, brush-up courses (0.6 ECTS)
- Introduction to R; PE&RC (2015)

Laboratory training and working visits (0.9 ECTS)
- Developing proposal to develop East African highland banana sub-model for the FIELD model; IITA Uganda, Godfrey Taulya (2015)

Invited review of journal manuscripts (3 ECTS)
- Agricultural Systems: farm typologies and sustainable intensification (2017)
- Agricultural Systems: modelling options for water efficiency (2019)
- Agricultural Systems: participatory evaluation of technologies (2020)

Competence strengthening / skills courses (3.1 ECTS)
- Effective behaviour in your professional surroundings; WGS (2018)
- Scientific writing; Into Languages (2019)

Scientific integrity/ethics in science activities (0.6 ECTS)
- Research integrity; WIAS (2017)

PE&RC Annual meetings, seminars and the PE&RC weekend (1 ECTS)
- PE&RC Midterm weekend (2019)
- Master class on legume nitrogen fixation (2019)
- PE&RC Last year weekend (2019)

Discussion groups / local seminars or scientific meetings (6.3 ECTS)

- Sustainable Intensification of Agricultural Systems, SIAS; WUR (2015-2017)
- IITA-Uganda seminars; Kampala, Uganda(2018-2019)
- Banana projects; WUR (2019-2021)

International symposia, workshops and conferences (5.4 ECTS)

- PROIntensAfrica mid-term evaluation workshop for in-depth case studies; oral presentation; Dakar, Senegal (2016)
- HumidTropics marketplace workshop for systems research; poster presentation; Ibadan, Nigeria (2016)
- Farming systems design conference; oral presentation; Montevideo, Uruguay (2019)

Societally relevant exposure (0.3 ECTS)

- Opinion article, de Volkskrant, Voedselzaak: waarom Keniaanse boeren wél 21ste eeuwse maïs verbouwen (2018)

Lecturing/supervision of practicals/tutorials (9 ECTS)

- Integrated natural resource management in organic agriculture: supervising NUANCES-FARMSIM practical (2015-2019)
- Analysing sustainability of farming systems: lecture and supervising NUANCES-FARMSIM practical (2016-2021)

BSc/MSc thesis supervision (6 ECTS)

- Analysing manure and urine management practises of cattle farmers in western Kenya
- Unbalanced investments? A characterisation of banana (*Musa* spp., group AAA-EA)-based farming systems in western Uganda

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