Exploring and assessing trade-offs, synergies and diversity for smallholder agriculture

Carl Joachim Timler

Propositions

1. Understanding of the heterogeneity of farms and farmers is the most essential aspect of analysing farming systems.
   (this thesis)

2. Farmers' perceptions are paramount for sustainable intensification.
   (this thesis)

3. Q Methodology is deservedly gaining acceptance in the agricultural sciences, because it rapidly bridges the knowledge gap between researchers' ideas and farmers' experiences.

4. The motives of scientists and companies working on gene-splicing methods like CRISPR-Cas should be less pecuniary.

5. Open Access Publishing Matters.

6. Multinational breeding companies shackle farmers with hybrid seeds by removing their abilities to save and select their own seeds.

7. The personality qualities of an 'internet troll' are useful in creating thesis propositions.

Propositions belongs to the thesis, entitled

"Exploring and assessing trade-offs, synergies and diversity for smallholder agriculture"

Carl Joachim Timler

Wageningen, 27th October, 2020

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Exploring and assessing trade-offs, synergies and diversity for smallholder agriculture

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for my mother

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Contents

Chapter 1
Introduction

Carl Timler

◀ Kenyan smallholder farmer picking tea leaves. Tea is a common cash crop in Vihiga, Western Kenya. Photo Neil Palmer, CIAT

TL:DR

- Diverse smallholder farmers are faced with multiple competing objectives to ensure their livelihoods within a land constrained setting.
- They also face nutritional challenges to keep their families fed well.
- Modelling Sustainable Intensification options for smallholder farmers allows exploration of opportunities to improve their diverse trajectories.
- Psychological capital is a construct that can be used to assess vulnerability to shocks.
- Participatory methods of interaction with smallholder farmers allows for more effective transfer of knowledge and provide tailor-made solutions for adoption.

1.1 Problem Statement

In the rural areas of Eastern and Southern Africa and Southern Asia, agriculture is the main activity of the inhabitants, and the vast majority of these are highly heterogenous smallholder farmers (SOFA, 2014, Lowder *et al.*, 2016; Makate *et al.*, 2018). In these areas, under-nutrition and malnutrition (coupled with low dietary diversity) are prevalent especially in women and children under five years old, due to high levels of extreme poverty (FAO, IFAD, UNICEF, WFP, WHO, 2019). Smallholder farming systems in themselves, are very complex and are nested within environments that are becoming increasingly more strained spatially, socially, financially and environmentally (Tittonell, 2014). These same systems are also responsible for producing 80% of the world's food (SOFA, 2014), and thus unravelling this complexity and understanding their constraints, is key to improving nutrition and livelihoods for the burgeoning populations in these areas.

Multiple Competing Objectives

The diverse smallholder farmers living in these regions and deriving their livelihoods from complex production systems, have multiple, competing objectives which increase the difficulty of making their daily decisions. These farmers currently face many resource constraints that potentially limit the options they can choose. Furthermore, the multitude and range of possibilities that could provide solutions to these challenges of constrained resources, and the potential multitudes of future configurations of their farming systems, can confound their ability to choose alternatives, or may simply take too much time and, with scarce resources to physically experiment with, prove daunting (Le Gal *et al.*, 2011). Blanket recommendations are likewise, not suitable to ameliorate these challenges, as these are diverse and complex farms and individual farmers require tailor-made solutions (Ronner, 2018; Yageta *et al.*, 2019) to fit their diverse, unique situations with its matching set of challenges.

Land Constraints

Ever decreasing farm sizes due to generational subdivision of farming land coupled with increasing population growth is a major constraint to these farming systems (Frelat *et al.*, 2016). There is no further room to expand their farming operations as all available agricultural land has already been utilized, or land that is remaining is of marginal to unsuitable potential, and is best left uncultivated (Kebede *et al.*, 2019). Furthermore, converting these low potential areas into agricultural land can drastically reduce the ecosystem services often provided by these (recovering) natural areas (Nyberg *et al.*, 2020). Large portions of land deemed unsuitable for agriculture due to steep slopes, extreme rockiness, shallow or poor soils have also been depleted of forests which have been cut for wood for sale as charcoal or for construction material, or suffer from erosion due to vegetation cover loss (Félix Lancelloti, 2019).

Nutritional Constraints

Hidden hunger with its accompanying micronutrient deficiencies (Remans *et al*., 2014) due to poor monotonous cereal based diets, reliance on the consumption of purchased processed and packaged foods of dubious nutritional quality, poor health care, all reinforce the vulnerability of these populations (Khan & Hoan, 2008; Lachat *et al*. 2009; Laillou *et al*., 2012). These deficiencies in proteins, vitamins and other micronutrients can cause severe and lifelong health issues and are the cause of nutrition related non-communicable diseases. Popkin (2003) also links these diseases to the change to a more western-type diet high in saturated fats, sugars and refined foods and low in fibre. Frison *et al*. (2005) calls for '*aggressive promotion of indigenous food*' in order to diversify diets to address the issue of global hunger and malnutrition.

Low Psychological Capital

These constraints creating adverse conditions, affect the psychological capital of these farmers as shown by Chipfupa and Wale (2018). Optimism, hope and self-confidence and resilience are four pillars upon which one can assess psychological capital. Luthans *et al*. (2007) defined psychological capital as "*an individual's positive psychological state of development and is characterized by: (1) having confidence (self-efficacy) to take on and put in the necessary effort to succeed at challenging tasks; (2) making a positive attribution (optimism) about succeeding now and in the future; (3) persevering toward goals and, when necessary, redirecting paths to goals (hope) in order to succeed; and (4) when beset by problems and adversity, sustaining and bouncing back and even beyond (resilience) to attain success*". Chipfupa & Wale (2018) used this to show that smallholder farmers with low psychological capital are less likely to succeed when faced with adversity. They are fragile, and unable to withstand shocks which translates to severe reductions in their livelihoods making them vulnerable. Knowledge empowers farmers. Knowledge improves psychological capital. Farmers who have greater optimism, hope, self-confidence and resilience are better equipped to withstand shocks and recover faster. In these regions unstable economies, political systems and failing infrastructure compound the challenges faced by these farmers. Jambo *et al*. (2019) show that reform, improved resilience or improvement in these systems will therefore need to come from within, from intrinsic motivations to improve. This needs to be supported not only by enabling environments (e.g. improved infrastructure) but also by supplying knowledge through extension.

Sustainable Intensification (SI)

One of the ways agricultural development can be characterized is, is as either extensification- or intensification-based. Extensification in the context of smallholder farming in Sub Saharan Africa and south Asia, is characterized by increasing the size of the cultivated lands (conversion from uncultivated land or restoration of degraded land) in order to increase production and is done where land (and labour) is freely available to do so. Intensification occurs where land is limited, typically when population pressure is high and with high pressure to intensify rapidly, some practices (e.g. high levels of mineral fertilizer application) could have negative consequences resulting in a decrease over time of, for instance, natural capital (e.g. decreased soil fertility). Thus, in order to ensure continued livelihood production from these systems, this intensification should occur sustainably. Pretty *et al*. (2011) writing on sustainable intensification in African agriculture, defined it as '*producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services*'. Mungai *et al*. (2016) present the potential for SI to improve farmer livelihoods, provided that this is accompanied by adequate extension support and complementary practices that improve the natural resources such as biological nitrogen fixation with legumes and improved residue management including composting. There are thus a number of diverse trajectories towards sustainable intensification such as using novel technologies, by enhancing farmers' knowledge or through improvement of a farm's natural capital.

Diverse Trajectories of Adoption and Adaption

Amongst the drivers of farmer diversity are farmers' different resource endowments, soils, farming systems and motivations, thus we can expect that these farmers would also be diverse in the strategies they have, and the sequences in which they would adopt a diverse set of (sustainable) agricultural intensification options (Giller *et al*., 2011). Thus tailor made solutions to match these different strategies are required. *In silico* exploration of these trajectories provides farmers with the knowledge of the effects of the diverse choices available, and enables them to plan their farming strategies, to optimize their multiple objectives. Further *in silico* exploration of subsequent model cycles of (sustainable) intensification can aid in creating more long-term trajectories. Thus we explore the diversity of production opportunities from a diverse basket of interventions.

1.2 Opportunities for Sustainable Intensification

Legume Integration

One of the opportunities for sustainable intensification is integration of legumes into maize based systems, either in rotations or as intercrops. Legume integration is widely promoted to improve human diets with additional protein, and to enhance soil fertility through biological nitrogen fixation (Vanlauwe *et al.*, 2019). This in turn enhances crop yields and biomass production (Nord *et al.*, 2020). The residues of maize and the leguminous crops are further desirable as animal feeds, compost and soil amendments. Thus, the integration of legumes combined with changes in resource use and allocation provide opportunities to improve farm productivity and household diets, whilst also reducing pressure on local ecosystems making it an excellent example of SI. Snapp *et al.* (2019) outline many promising options for legume integration in Sub-Saharan Africa using for example, legumes with temporarily complementary growth habits as 'Doubled Up Legume" intercrops. In their review of cereal legume integration studies, Franke *et al.* (2018), show widespread benefits such as improvement of grain yields, but also improvements in soil organic matter, and reduction of the parasitic weed Striga.

Conservation Agriculture

Another example of SI is Conservation Agriculture (CA) that is based upon three principles; reduced or no tillage of soil, the use of layers of crop residues as mulch to cover the soil and the practice of crop rotations (Ngwira *et al.*, 2020). CA is widely applied in Sub Saharan Africa and Southern Asia and has shown to improve soil fertility, reduce moisture loss through the mulch layers, and to promote soil life (Page *et al.*, 2020). Combining CA technologies with other complementary practices can further enhance the effectiveness of CA in the short to medium term (Thierfelder *et al.*, 2018).

Nutrition Sensitive Interventions

A third approach to SI is nutrition-sensitive agriculture that can potentially address the challenges of micronutrient deficiencies caused by hidden hunger (Remans *et al.*, 2014). Thompson and Amoroso (2013) cited in Powell *et al.* (2013) define nutrition-sensitive agriculture as *'agriculture that effectively and explicitly incorporates nutrition objectives, concerns and considerations to achieve food and nutrition security* (FAO/AGN)'. Interventions to improve nutrition were classified into three distinct types according to a review of 42 different interventions by Fiorella *et al.* (2016). The three types were enhancement, diversification and substitution and they differed by the extent to which the intervention altered the farmer's current livelihood strategy or their pattern of food consumption. Diversifying agricultural production to create a more diverse farm production system for smallholder farmers is viewed as a method to enhance household nutrition through improving their access to a wide range of food crops (Powell *et al.* 2013; Sibhatu *et al.* 2015). A farming system with more agrobiodiversity is shown by Oudour *et al.* (2019) to have an increased system capacity to provide a range of nutrient functions for the farm household members. Hence, within the farming system, diversifying the (crop, fruit tree and livestock) production can potentially be a lever to improve dietary diversity especially in subsistence farming systems.

There are a number of other promoted opportunities for sustainable intensification. The integration of livestock on farms improves social, environmental and economic farm performance (Martin *et al.*, 2020) especially with improved feeds and forages (Paul, 2019). Some opportunities are more nature-based such as agroforestry, where the natural resources are improved through enhanced ecosystem services as outlined by Nyberg *et al.* (2020), whilst others are more focused on greater use of fertilizers and hybrid seeds inputs to improve production of staple grains (Jindo *et al.*, 2020).

1.3 Knowledge Transfer through Smallholder Farm Modelling

In summary, farmers in the rural areas of Eastern and Southern Africa and Southern Asia have limited space and resources which physically prevent actual experimentation and therefore such activities are not present or feasible (Le Gal *et al.*, 2011). However, *in silico* experimentation and scenario testing with realistic whole-farm bio-economic models provides a way of mapping the solution spaces in order to illuminate and highlight optimal solutions for future development of these diverse farming systems. The trade-offs, and more importantly the synergies, that emerge out of the solution spaces can illuminate the potential forward trajectories of these vulnerable smallholders.

The number of studies on whole-farm modelling has been increasing since the turn of the century (van Wijk *et al.* 2014). They propose the need for inclusion of food security and nutrition indicators[1] and go on further to call for more generic and less site-specific models to allow for more diverse smallholder farming systems from different geographic locations to be analysed.

Le Gal *et al.*, (2011), incorporated the DEED cycle into farming systems modelling. The DEED cycle is an iterative learning cycle incorporating four steps namely Describe, Explain, Explore and Design (Giller *et al.*, 2008).

1. Since 2014, nutrition and household indicators have been added to the FarmDESIGN model (Ditzler *et al.*, 2019, Estrada-Carmona *et al.*, 2020).

Firstly the system is Described, which then Explains the performance of the current system. Improvements to the system can be Explored and selected improvements incorporated into a Design. Groot *et al.* (2017) further expanded this cycle to be more inclusive (INDEED) such that; smallholder' cultures, values and priorities are *in*cluded, there is *in*teraction with relevant stakeholders, ecological processes are *in*tegrated, all consequences are *in*spected and positive outcomes are *in*vested in. Martin *et al.* (2013) also call for more inclusion of participatory processes into smallholder modelling. Thus, using a three-way participatory learning approach rather than a linear one (Figure 1.1), and with the inclusion of the INDEED cycle, iterative learning cycles of co-learning with participatory modelling can be implemented between the researchers' bio-technical modelling, the extension provided by advisors and the knowledge of the farmers to transfer design support and knowledge to farmers (Figure 1.1).

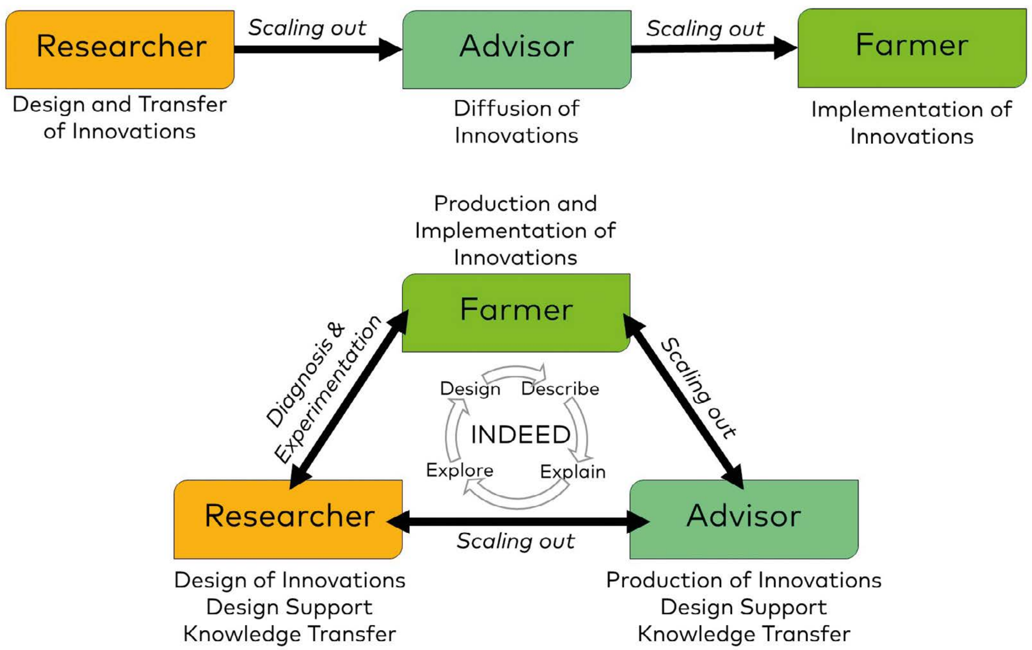

Figure 1.1 A linear transfer of knowledge from Researcher to Farmer (above) as opposed to a more effective three-way participatory transfer of knowledge and design support (below), incorporating the INDEED learning cycle (Groot *et al.*, 2017), between Researchers, Advisors and Farmers (adapted from Le Gal *et al.*, 2011).

Such whole-farm models thus require large sets of data on many aspects of the farm performance. Although much research has been done, Jones *et al.* (2016) indicate, the greatest needs for further work on smallholder farm modelling lie not in the conceptual frameworks they are built upon but rather on the gross lack of, or inaccessibility of, data sets to model with, and that there are barriers connecting practitioners with model results. Thus collaboration is required within agricultural systems modelling siloes in order to keep up with the demands of new ICT developments globally (Janssen *et al.*, 2016). Focus should be placed on the needs of the beneficiaries using inclusive learning cycles. Open source publications and data sharing[2] as well as adherence to good modelling practice will allow for standardized modules that can be widely used to improve smallholders' livelihoods.

Farm systems are nested within a hierarchical system with many scales (Fresco & Westphal, 1988). These multiple scales need to be integrated into farming systems research (Kanter *et al.*, 2016). They propose that data should be aggregated at lower scales to improve modelling at higher levels. The COMPASS suite of models, to which FarmDESIGN belongs, were cited as a promising framework upon which scales have already been integrated in a bottom-up approach whereby model output from lower levels informs higher levels. Kanter *et al.* (2016) also cite crowdsourcing of data from farmers as a promising direction for new research, to allow for further co-innovation with and for smallholders. Malthusian theory (1798) states that when resources are limited, populations will collapse or decline due to a lack of food. In contrast, Ester Boserup[3] (1965) theorized that in these situations, where resources become limiting, populations will discover new technologies to intensify production, necessity being the "mother of all inventions". Recent development in Africa is focusing on more *in silico* innovations for smallholder farmer development (Fabregas *et al.*, 2019).

In Asia and Africa, mobile phone penetration is over 75% with a growing proportion of these as (internet connected) smartphones (Fabregas *et al.*, 2019). The lack of infrastructure in many rural areas such as electricity powerlines or telephone lines, meant that in these areas solar power and mobile phones were far more suitable and quicker to use than physical lines on poles. This has meant that mobile phone penetration into the African continent has boomed, with many also owning smartphones now (Figure 1.2).

2. All publications and datasets from this PhD study are open source.

3. Ester Boserup was, in 1978, the first women ever to receive an Honorary Doctorate from Wageningen University, for her work in agricultural development.

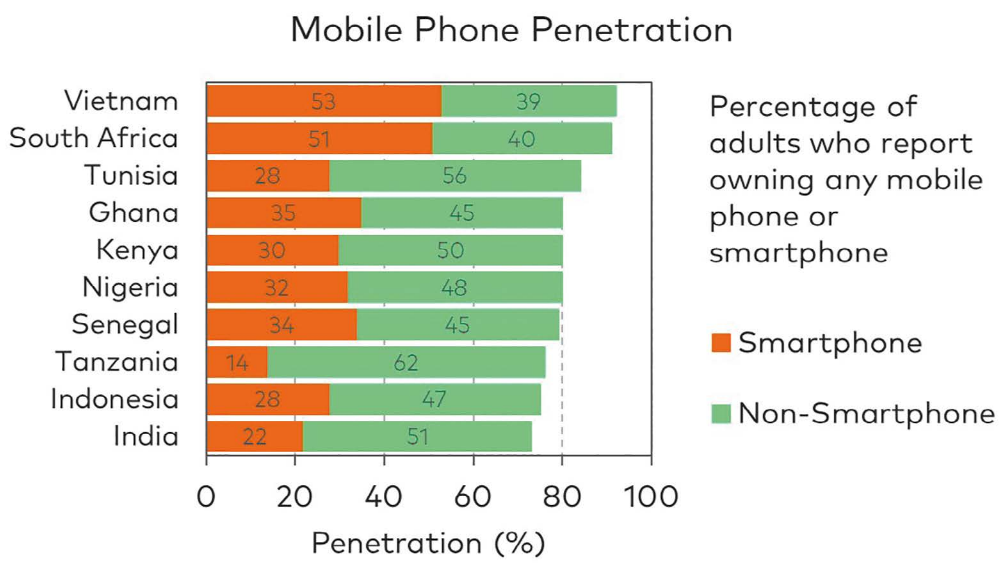

Figure 1.2: Mobile phone penetration in countries in Africa and Asia (adapted from Fabregas *et al.*, 2019), [data from Pew Global Attitudes Survey, Spring 2017: https://www.pewresearch.org/global/dataset/spring-2017-survey-data/].

Opportunities are thus present for smallholder farmers to benefit from the ability for the rapid dissemination of knowledge through novel mobile applications and connectivity to platforms for marketing their produce enabling development to quickly be scaled out (Figure 1.1).

1.4 Thesis Framework

In this thesis we use whole-farm modelling to find solutions for informing sustainable intensification of smallholder farmers in Sub Saharan Africa and Southern Asia. The INDEED cycle (Figure 1.1), is chosen as the framework upon which this research has been structured (Figure 1.3). This learning cycle is also built into the user interface structure of the model FarmDESIGN, with four windows Describe/Design, Explain, Evaluate and Explore.

In order to assess diversity and place farmers in meaningful categories, we use typology creation. We build on the typology studies of Tittonell, *et al.*, (2010) to describe and explain the hypothesized diversity one could expect in a population of smallholders. The heterogeneity is simplified into manageable similar clusters

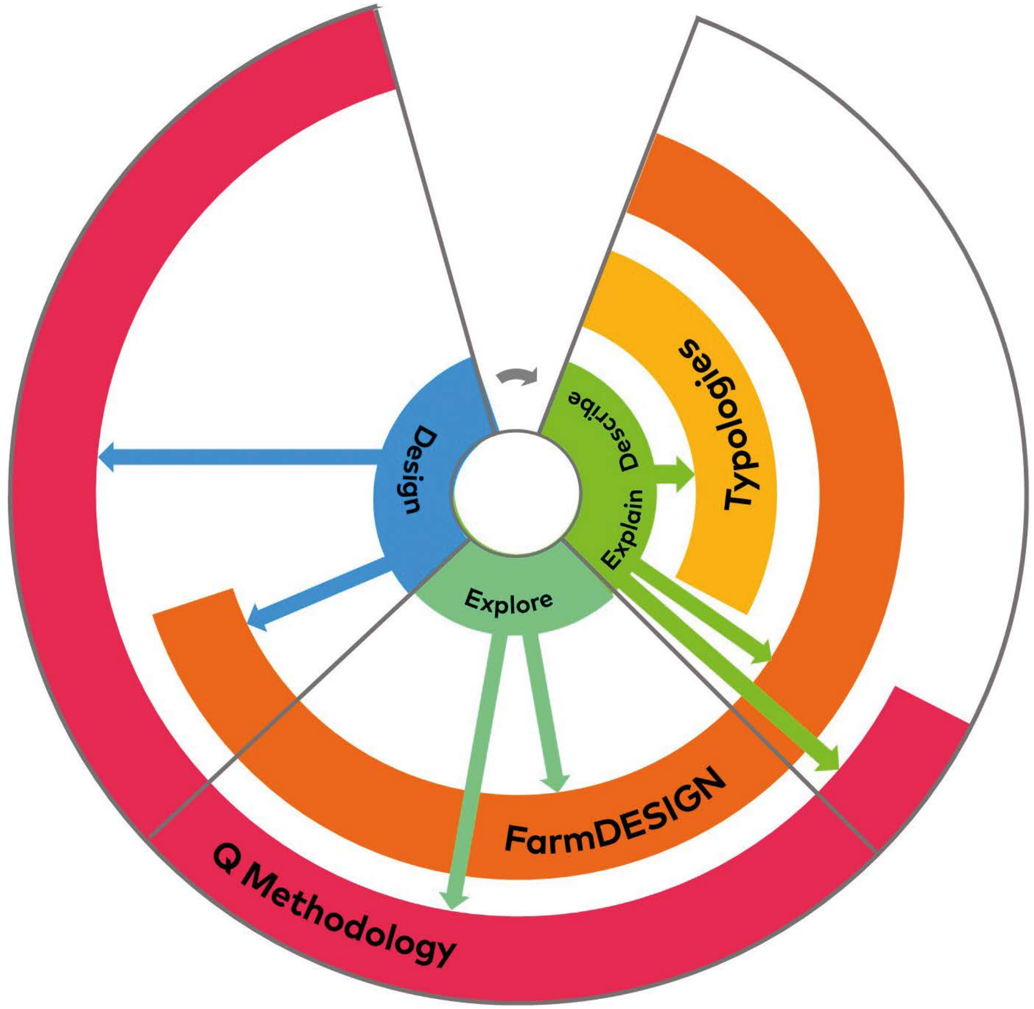

Figure 1.3 Thesis Framework indicating the DEED cycle (Describe, Explain, Explore and Design) and the connection to the methodologies and model used.

of farmers that can then be modelled, as creation of fewer working models is more efficient when scaling out technologies that impact different farmers differently. This aids in making tailor made interventions for smallholders.

Participatory modelling, using the model FarmDESIGN, provides farmers insight and informs researchers of farmers' experiences, producing feasible modelling outcomes and affordances that display synergies between the participants and the researcher (Ditzler *et al.*, 2018). Cycles of inclusive participatory co-learning along the INDEED cycle enable farmers to plan their trajectories and strategically implement changes.

To assess the diversity of strategies that smallholder farmers could use, and to aid formation of homogenous participatory groups of farmers, Q Methodology can be used. Q Methodology explains diversity by clustering like-minded individuals who feel similarly about a certain topic (Stephenson, 1935). Since its inception in the second half of the 20th Century, it has been increasingly used to examine smallholder farmer perceptions, for example in the recent studies by Dingkhun *et al.* (2020) and Góngora *et al.* (2019). Dingkhun *et al.* (2020) show how Q Methodology can be used to define farmers' demands for soil functions and how this clustering allows community-led transition pathways to be explored. Góngora *et al.* (2019) demonstrate the use of Q Methodology to elucidate farmer trajectories and the drivers of these trajectories. Bringing farmers together and supporting them in groups also aids in mutual support through labour exchanges to implement innovations. This then in turn, further fosters adaptions and further experimentation by these farmer groups.

1.6 Research Objectives

The main objective of this thesis is to explore and reveal the diversity in windows of opportunity and tradeoffs for smallholder farmer households whereby their livelihoods can be improved in terms of improved productive, nutritional, socio-economic and environmental outcomes. Different windows of opportunities will be related to heterogeneities in access to, and use of, the variety of available technologies for sustainable intensification, in farm endowment and strategy, and in intrinsic motivation and perspectives. The subsidiary objectives are;

1. To develop and apply methods to analyse and capture the diversity of smallholder farm households, in particular through typology construction, and to determine the effect of farmers' objectives, and of model assumptions and variable selection on the outcome of such methods.
2. To quantify the differences in trade-offs faced by farmers who differ in objectives and endowment, and who face different constraints, thus belonging to contrasting farm types and employing dissimilar strategies, and to identify which novel technologies are most suitable for the various socio-economic contexts/niches.
3. To explore trade-offs between possibilities to close nutritional gaps and improve human nutrition and the improvement of farmer livelihoods in smallholder farm(er) landscapes along a trajectory of market orientation.
4. To analyse contrasting trajectories of livelihood improvement in terms of strengthening economic, physical and natural capital, and changing labour inputs, using legume integration and crop diversification as examples of sustainable intensification strategies.

1.7 Research Questions

To achieve these objectives the following research questions are posed;

1. How to capture the diversity of heterogeneous smallholder farmer households through construction of typologies, and to what extent does the selection of variables affect the outcome of these typologies?
2. If the differences in trade-offs faced by different types of farmers can be quantified, how can this aid the selection of suitable novel technologies for these different farm types?
3. To what extent can nutrition gaps be closed, and human nutrition and provisioning of ecosystems services be improved by optimization using a whole-farm model?
4. How can the trajectories of livelihood improvements of diverse smallholder farmer types be analysed and improved by strengthening economic, physical and natural capital, and by changing labour inputs, through the use of legume integration and crop diversification, and can this be aided by suitable and accurate output from a farm level model?

1.8 Research Methodologies

The following methodologies will be used to answer the research questions;

1. Testing the robustness of typologies
Data from a baseline survey conducted in the eastern province of Zambia in 2011/2012 covering 811 households in three districts was used to construct typologies. Typologies were constructed. To address RQ 1, the results from the three typologies were contrasted and analysed for overlap, and are discussed

in the context of the formulated hypothesis-based approach for typology construction in chapter 2.

2. Comparison of trade-offs faced by different farm types at the farm scale
Data from the typologies performed above was used to select representative farmers in each of the three districts (n=15) in the eastern province of Zambia to be visited for a detailed characterization. A semi-structured survey was used to collect detailed farm data. These farming systems were constructed in the model FarmDESIGN. Expert knowledge from local stakeholders created the basis upon which the solution spaces for the different farm types, which were explored using a Pareto-based multi-objective optimization algorithm (Groot *et al.*, 2012). The outer surfaces of the solution spaces represent the trade-off areas. These trade-off areas are compared between farm types and presented in chapter 3.

3. Exploring trade-offs between improved human nutrition and farmer livelihoods
Four contrasting farms in Kenya and Vietnam along a gradient of market orientation were modelled using data collected in semi-structured interviews and through FGD's[4], 24hr Recalls and FFQ[5]. Assessment of the nutrition status of the farm households was done using the nutrition indicators in FarmDESIGN for the households. Scenario explorations were performed using innovations of traditional leafy vegetables using FarmDESIGN to examine the trade-offs between human nutrition and improved livelihoods along the gradient of market orientation between the case study sites. These are presented in chapter 4.

4. Analysis of contrasting trajectories of livelihood improvement
Four trajectories of intensification were hypothesized including: (i) technological based intensification disregarding natural capital, (ii) technology based intensification enhancing natural capital, (iii) labour based intensification and (iv) a combination of ecological and technologically based intensification. Q Methodology was used to examine the managerial strategies (factors) of diverse smallholder farmers in central Malawi and to link the emerging factors to the trajectories. These strategies and matching trajectories are presented in chapter 5.

4. FGD: Focus Group Discussion
5. FFQ: Food Frequency Questionnaire

1.9 Thesis Outline

In this chapter, I introduced the problems facing smallholders and outlined the options for the sustainable intensification of these farming systems. I proposed the use of participatory smallholder farm modelling using a whole-farm model as an option to inform smallholder exploration into the diverse options available. I presented the research objectives, questions and methodologies to be used as well as this thesis outline.

In chapter two, we show how farm diversity can be captured using hypothesis-based typologies. We present innovative methodological framework for farming system typology development using the development of typologies of farming systems of the Eastern province of Zambia as a case study.

In chapter three we use the whole-farm model FarmDESIGN to build farm models of the different farmer types presented in Chapter 2. We explore the options for sustainable intensification through legume integration in these different farm types in the Eastern province of Zambia showing how different interventions suit different farm types.

In chapter four we use FarmDESIGN to model smallholder farms along a gradient of market intervention in Western Kenya and Northwestern Vietnam. We explore nutrition-sensitive agricultural interventions of novel traditional leafy green vegetables to examine the possibilities of closing nutrition gaps whilst simultaneously improving economic performance and reducing labour requirements at a farm level.

In chapter five we use Q methodology to examine the diverse strategies steering managerial intensification pathways of smallholder farmers in Central Malawi. We link these pathways to four hypothesized intensification trajectories.

In the final chapter, the general discussion, I discuss the results and implications of this body of research.

Chapter 2
Capturing farm diversity with hypothesis-based typologies: an innovative methodological framework for farming system typology development

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◄ A Zambian farmer proudly posing for a photo in his cassava field. Photo: Mirja Michalscheck

Abstract

Creating typologies is a way to summarize the large heterogeneity of smallholder farming systems into a few farm types. Various methods exist, commonly using statistical analysis, to create these typologies. We demonstrate that the methodological decisions on data collection, variable selection, data-reduction and clustering techniques can bear a large impact on the typology results. We illustrate the effects of analysing the diversity from different angles, using different typology objectives and different hypotheses, on typology creation by using an example from Zambia's Eastern province. Five separate typologies were created with principal component analysis (PCA) and hierarchical clustering analysis (HCA), based on three different expert-informed hypotheses. The greatest overlap between typologies was observed for the larger, wealthier farm types but for the remainder of the farms there were no clear overlaps between typologies. Based on these results, we argue that the typology development should be guided by a hypothesis on the local agriculture features and the drivers and mechanisms of differentiation among farming systems, such as biophysical and socio-economic conditions. That hypothesis is based both on the typology objective and on prior expert knowledge and theories of the farm diversity in the study area. We present a methodological framework that aims to integrate participatory and statistical methods for hypothesis-based typology construction. This is an iterative process whereby the results of the statistical analysis are compared with the reality of the target population as hypothesized by the local experts. Using a well-defined hypothesis and the presented methodological framework, which consolidates the hypothesis through local expert knowledge for the creation of typologies, warrants development of less subjective and more contextualized quantitative farm typologies.

2.1 Introduction

Smallholder farming systems are highly heterogeneous in many characteristics such as individual farming households' land access, soil fertility, cropping, livestock assets, off-farm activities, labour and cash availability, socio-cultural traits, farm development trajectories and livelihood orientations e.g. Tittonell *et al.*, 2010; Zingore *et al.*, 2007. Farm typologies can help to summarize this diversity among farming systems. Typology construction has been defined as a process of classification, description, comparison and interpretation or explanation of a set of elements on the basis of selected criteria, allowing reduction and simplification of a multiplicity of elements into a few basic/elementary types (Legendre, 2005 cited by Larouche, 2011). As a result, farm typologies are a tool to comprehend the complexity of farming systems by providing a simplified representation of the diversity within the farming system by organizing farms into quite homogenous groups, the farm types. These identified farm types are defined as a specific combination of multiple features (Brossier and Petit, 1977; Capillon, 1993; Jollivet, 1965).

Capturing farming system heterogeneity through typologies is considered as a useful first step in the analysis of farm performance and rural livelihoods (Giller *et al.*, 2011; Tittonell, 2014). Farm typologies can be used for many purposes, for instance i) the selection of representative farms or prototype farms as case study objects (e.g. Alary *et al.*, 2016; Andrieu *et al.*, 2015; Vayssières *et al.*, 2011); ii) the targeting or fine-tuning of interventions, for example by identifying opportunities and appropriate interventions per farm type (e.g. Douxchamps *et al.*, 2016; Hauswirth *et al.*, 2015; Kuivanen *et al.*, 2016a; Laurent *et al.*, 1999; Lau *et al.*, 2001; Timler *et al.*, 2017); iii) for the extension of technologies, policies or ex-ante impact assessments to larger spatial or organizational scales (up-scaling and/or out-scaling) (e.g. Andersen *et al.*, 2007; Ewert *et al.*, 2011; Riedsma *et al.*, 2010; Reidsma *et al.*, 2011); and iv) to support the identification of farm development trajectories and evolution patterns (e.g. Albaladejo and Duvernoy, 1997; Chopin, Blazy and Doré, 2015; Falconnier *et al.*, 2015; Perrot, Landais and Pierret, 1995; Rueff *et al.*, 2012; Valbuena *et al.*, 2015).

Various approaches can be used to develop farm typologies (Landais, 1988). The identification of criteria defining a farm type can be based on the knowledge of local stakeholders such as extension workers and/or farmers, or derived from the analysis of data collected using farm household surveys which provide a large set of quantitative and qualitative variables to describe the farm household system (Kuivanen *et al.*, 2016b). Perrot *et al.* (1995) proposed to define "aggregation poles" with local experts, i.e. virtual farms summarising the discriminating characteristics of a farm type, which can then be used as reference for the aggregation (manually or with statistical techniques) of actual farming households into specific farm types. Based on farm surveys and interviews, Capillon (1993) used a (manual) step-by-step comparison of farm functioning to distinguish different types; this analysis focused on the tactical and strategic choices of farmers and on the overall objective of the household. Based on this approach, farm types were created using statistical techniques to first group farms according their structure, then within each of these structural groups, define individual farm types on the basis of their strategic choices and orientation (Monicat *et al.*, 1992). Landais *et al.* (1988) favoured the comparison of farming practices for the identification of farm types. Kostrowicki and Tyszkiewicz (1970) proposed the identification of types based on the inherent farm characteristics in terms of social, organizational and technical, or economic criteria, and then representing these multiple dimensions in a typogram, i.e. a multi-axis graphic divided into quadrants, similar to a radar chart. Nowadays, statistical techniques have largely replaced the manual analysis of the survey data and the manual farm aggregation/comparison. Statistical techniques using multivariate analysis are one of the most commonly applied approaches to construct farm typologies (e.g. Alary *et al.*, 2002; Blazy *et al.*, 2009; Bidogeza *et al.*, 2009; Chavez *et al.*, 2010; Cortez-Arriola *et al.*, 2015; Köbrich, Rheman and Khan, 2003; Mbetid-Bessane *et al.*, 2003; Pacini *et al.*, 2014). These approaches apply data-reduction techniques, i.e. combining multiple variables into a smaller number of 'factors' or 'principal components', and clustering algorithms on large databases.

Typologies are generally conditioned by their objective, the nature of the available data, and the farm sample (Perrot and Landais, 1993). Thus, the methodological decisions on data collection, variable selection, data-reduction and clustering have a large impact on the resulting typology. Furthermore, typologies tend to remain a research tool that are not often used by local stakeholders (Perrot and Landais, 1993). In order to make typologies more meaningful and used, we argue that typology development should involve local stakeholders (iteratively) and be guided by a hypothesis on the local agricultural features and the criteria for differentiating farm household systems. This hypothesis can be based on perceptions of, and theories on farm household functioning, constraints and opportunities within the local context, and the drivers and mechanisms of differentiation (Rey, 1989; Whatmore *et al.*, 1987). Drivers of differentiation can include bio-physical conditions, and the variation therein, as well as socio-economic and institutional conditions such as policies, markets and farm households integration in value chains.

The objective of this article is to present a methodological approach for typology construction on the basis of an explicit hypothesis. Building on a case study of Zambia, we investigate how typology users' – here, two development projects – objectives and initial hypothesis regarding farm household diversity, impacts typology construction and consequently, its results. Based on this we propose a methodological framework for typology construction that utilizes a combination of expert knowledge, participatory approaches and multivariate statistical methods. We further discuss how an iterative process of hypothesis-refinement and typology development can inform participatory learning and dissemination processes, thus fostering specific adoption in addition to the fine-tuning and effective out-scaling of innovations.

2.2 Materials and Methods

Typology construction in the Eastern province, Zambia

We use a sample of smallholder farms in the Eastern province of Zambia to illustrate the importance of hypothesis formulation in the first stages of the typology development. This will be done by showing the effects of using different hypotheses on the typology construction process and its results, while using the same dataset. Our experience with typology construction with stakeholders in Zambia made clear that i) the initial typology objective and hypotheses were not clearly defined nor made explicit at the beginning of the typology development, and ii) iterative feedbacks with local experts are needed to confirm the validity of the typology results.

The typology construction work in the Eastern Province of Zambia (Figure 2.1) was performed for a collaborations between SIMLEZA (Sustainable Intensification of Maize-Legume Systems for the Eastern Province of Zambia) and Africa RISING (Africa Research in Sustainable Intensification for the Next Generation; https://africa-rising.net/); two research for development projects operating in the area. Africa RISING is led by IITA (International Institute of Tropical Agriculture; http://www.iita.org/) and aims to create opportunities for smallholder farm households to move out of hunger and poverty through sustainably intensified farming systems that improve food, nutrition, and income security, particularly for women and children, and conserve or enhance the natural resource base. SIMLEZA is a research project led by CIMMYT (International Maize and Wheat Improvement Center; http://www.cimmyt.org/) which, amongst other objectives, seeks to facilitate the adoption and adaptation of productive, resilient and sustainable agronomic practices for maize-legume cropping systems in Zambia's Eastern Province. The baseline survey data that was used was collected by the SIMLEZA project in 2010/2011. The survey dataset was used to develop three typologies using three different objectives, to investigate the effects that different hypotheses have on typology results.

Figure 2.1 Map of the study area: Lundazi, Chipata and Katete districts (in violet), Eastern Province of Zambia.

Zambia's Eastern Province is located on a plateau with flat to gently rolling landscapes at altitudes between 900 to 1 200 m above sea level. The growing season lasts from November to April, with most of the annual rainfall of about 1 000 mm falling between December and March (Simuko *et al.*, 2007). Known for its high crop production potential, Eastern Zambia is considered the country's 'maize basket' (Aregheore, 2016). However, despite its high agricultural potential (Table 2.1), the Eastern Province is one of the poorest regions of Zambia, with the majority of its population living below the US$1.25 day^{-1} poverty line (Malapit *et al.*, 2014).

The SIMLEZA baseline survey captured household data of about 800 households in three districts, Lundazi, Chipata and Katete (Figure 2.1). Although smallholder farmers in these districts grow similar crops, including maize, cotton, tobacco, and legumes (such as cowpeas and soy beans), the relative importance of these crops, the livestock herd size and composition, and their market-orientation differ substantially, both between and within districts.

The densely populated Chipata and Katete districts (respectively, 67.6 and 60.4 persons km^{-2}) (CSO, 2011) located along the main road connecting the Malawian and Zambian capital cities are characterised by highly intensive land use, relatively small land holdings and relatively small livestock numbers. The Lundazi district, by contrast, has rather extensive land-use and a low population density (22.4 persons km^{-2}) (CSO, 2011), and is characterised by large patches of unused and fallow lands, which are reminiscent of land-extensive slash and burn agriculture.

Alternative typology objectives and hypotheses

Iterative consultations with some of the SIMLEZA-project members in Zambia, informed the subsequent construction of three farm household typologies, all based on different objectives. The objective of the first typology (T1) was to classify the surveyed smallholder farms on the basis of the most distinguishing features of the farm structure (including crop and livestock components). The first hypothesis was that farm households could be grouped by farm structure, captured predominantly in terms of wealth indicators such as farm and herd size. When the resulting typology was not deemed useful by the local project members (because it did not focus enough on the cropping activities targeted by the project), a second typology was constructed with a new objective and hypothesis. The objective of the second typology (T2) was to differentiate farm households in terms of their farming resources (land and labour) and their integration of grain legumes (GL). The second hypothesis was that farming systems could be grouped according to their land and labour resources and their use of legumes, highlighting the labour and land resources (or constraints) of the groups integrating the most legumes. But again the resulting typology did not satisfy the local project members; they expected to see clear differences in the typology results across the three districts (Lundazi, Chipata and Katete), as the districts represented rather different farming contexts. Thus for the third typology (T3), the local partners hypothesized that the farm types and the possibilities for more GL integration would be strongly divergent for the three districts, due to differences in biophysical and socio-economic conditions (Table 2.1). The hypothesis used was that the farm households could be grouped according to their land and labour resources and their use of legumes and that the resulting types would differ between the three districts. Therefore, the objective of the third typology focused on GL integration as for T2, but for the three districts separately (T3-Lundazi, T3-Chipata and T3-Katete).

Table 2.1 Main farming characteristics of three districts of Eastern Province of Zambia, Lundazi, Chipata and Katete

Characteristics	Unit	Lundazi	Chipata	Katete
Climate	-	Tropical Savanna	Tropical Savanna	Humid Subtropical
Precipitation[1]	*mm year^{-1}*	896	1 023	1 090
Average temperature[2]	°C	19.1 - 27.0	18.0 - 25.3	17.4 - 25.6
Altitude	*masl*	1 143	1 140	1 060
Population density[3]	*capita km^{-2}*	22.4	67.6	60.4
Main Food crops[4]	*from most to least frequent*	Maize, Groundnut & Beans	Maize, Groundnut & Beans	Maize, Groundnut & Cowpea
Main Cash crops[4]	*from most to least frequent*	Cotton, Sunflower & Tobacco	Sunflower, Cotton & Tobacco	Cotton, Sunflower & Tobacco
Livestock kept[4]	*from most to least frequent*	Chickens, Cattle, Pigs & Goats	Chickens, Pigs, Goats & Cattle	Chickens, Pigs, Cattle & Goats

1 Average precipitation (cumulated annual rainfall) from weather data was collected between 1982 and 2012 . Source: http://en.climate-data.org/region/1612/;
2 Lowest monthly average temperature and warmest monthly average temperature. Source: http://en.climate-data.org/region/1612/;
3 Source: http://www.zamstats.gov.zm/;
4 Sources: SIMLEZA Baseline Survey 2011-2012.

Multivariate analysis on different datasets

On the basis of the household survey dataset, five sub-databases were extracted which corresponded to the three subsets of variables chosen to address the different typology objectives (Table 2.2). The first two sub-databases included all three districts (T1 and T2) and the last three sub-databases corresponded to the subdivision of the data per district (T3). In each sub-database, some surveyed farms were identified as outliers and others had missing values; these farms were excluded from the multivariate analysis. A Principal Component Analysis (PCA) was conducted to reduce each dataset into a few synthetic variables, i.e. the first principal components (PCs). This was followed by an Agglomerative Hierarchical Clustering using the Ward's minimum-variance method, which was applied on the outcomes of the PCA (PCs' scores) to identify clusters. The Ward's method minimizes within-cluster variation by comparing two clusters using the sum of squares between the two clusters, summed over all variables (Hair *et al.*, 2010). The number of clusters (i.e. farm types) was defined using the dendrogram shape, in particular the decrease of the dissimilarity index ("Height") according to the increase of the number of clusters. The resulting types were interpreted by the means of the PCA results and put into perspective with the knowledge of the local reality. All the statistical analyses were executed in R (version 3.1.0, ade4 package; (Dray and Dufour, 2007)).

Table 2.2 Surveyed variables from the Eastern Province of Zambia and for the three districts (Lundazi, Chipata and Katete) and the variables used for the three Eastern Zambia typologies (T1, T2 and T3)

Variables				T1 Crop-livestock structure	T2 Farming resources and legume use	T3	Eastern Province	Lundazi	Chipata	Katete
Category	**Code**	**Description**	**Unit**				**Mean** (min-max)	**Mean**	**Mean**	**Mean**
Structure	*hhsize*	Number of member in the household	number	x			6.9 (1 - 20)	7.4	6.9	6.3
	oparea	Total operated area by the farm	ha	x	x	x	4.8 (0.02 - 35)	6.1	3.9	4.6
	tlu	Total tropical livestock unit	tlu	x	x	x	3.1 (0 – 29)	3.5	2.3	4.1
Livestock	*cattle*	Number of cattle	tlu				2.1 (0 - 24)	2.8	1.3	2.6
	cattleratio	Share of cattle in the total herd	–	x			0.36 (0 - 1)	0.43	0.27	0.43
	smallrum	Number of small ruminants (goats & sheep)	tlu				0.2 (0 - 5)	0.2	0.2	0.2
	smallrumratio	Share of small ruminants in the total herd	–	x			0.10 (0 - 1)	0.07	0.17	0.04
	pig	Number of pigs	tlu				0.6 (0 - 8)	0.5	0.6	1.1
	pigratio	Share of pigs in the total herd	–	x			0.23 (0 - 1)	0.15	0.24	0.34
	chicken	Number of chickens	tlu				0.1 (0 - 1.8)	0.1	0.1	0.1
	chickenratio	Share of poultry in the total herd	–	x			0.25 (0 - 1)	0.30	0.28	0.12
Labour	*totlabour*	Total labour use in the farm per year	hours	x	x	x	613 (7 – 5 531)	642	624	546
	hiredcost	Total hired cost per year	kZKW	x	x	x	236 (0 – 2 470)	354	169	173
	femratio	Share of the total labour done by women	–			x	0.52 (0 - 1)	0.52	0.51	0.53
	preplabrat	Share of the total labour allocated for land preparation	–		x	x	0.16 (0 - 1)	0.17	0.18	0.13
	weedlabrat	Share of the total labour allocated for weeding	–		x	x	0.33 (0 - 0.8)	0.31	0.33	0.38
	harvlabrat	Share of the total labour allocated for harvesting	–				0.33 (0 - 0.9)	0.30	0.34	0.36
	shelabrat	Share of the total labour allocated for threshing and shelling	–				0.17 (0 - 0.8)	0.22	0.15	0.13
Income	*totincome*	Total income per year	kZKW			x	10 522 (0 – 112 751)	14 292	7 400	9 701
	cropincome	Income generated per year from cropping activities	kZKW	x	x		6 749 (0 – 94 852)	9 553	4 205	7 063
	offincome	Income generated per year from off-farm activities	kZKW	x	x		3 256 (0 – 96 000)	4 456	2 770	2 215
	anlincome	Income generated per year from livestock activities	kZKW			x	517 (0 – 31852)	682	425	424
	cropincratio	Share of the total income generated per year by cropping activities	–			x	0.69 (0 - 1)	0.71	0.64	0.74
	anlincratio	Share of the total income generated per year by livestock activities	–				0.08 (0 - 1)	0.06	0.09	0.07
	offincratio	Share of the total income generated per year by off-farm activities	–				0.24 (0 - 1)	0.23	0.27	0.19

kZKW = 1000 x ZKW (Zambian Kwacha); 1 US$ ≈ 13 100 ZKW

Table 2.2 Continuation

Variables				T1 Crop-livestock structure	T2 Farming resources and legume use	T3	Eastern Province	Lundazi	Chipata	Katete
Category	**Code**	**Description**	**Unit**				**Mean** (min-max)	**Mean**	**Mean**	**Mean**
Legume	*legratio*	Percentage of the total operated area allocated for leguminous crops	%		x	x	20.1 (0 - 100)	7.4	6.9	6.3
	legexp	Number of years of experience on leguminous cropping	year		x		6.4 (0 - 73)	6.1	3.9	4.6
	legscore	Farmer evaluation of his/her leguminous cropping activities as a measure of their satisfaction	_		x		4.0 (0 - 5)			

kZKW = 1000 x ZKW (Zambian Kwacha); 1 US$ ≈ 13 100 ZKW

2.3 Results and discussion on the contrasting typologies

Of the five PCAs, the first four principal components explained between 55% and 64% of the variability in the five sub-databases (64, 55, 55, 57 and 62% for respectively T1, T2, and T3-Lundazi, T3-Chipata and T3-Katete). The four PCs are most strongly correlated to variables related to farm structure, labour use and income. The variables most correlated with PC1 were the size of the farmed land (*oparea*; five PCAs), the number of tropical livestock units (*tlu*; four PCAs), the cost of the hired labour (*hirecost*; four PCAs) and total income or income generated by cropping activities (*totincome* or *cropincome*; five PCAs) (Figures 2.2, 2.3 and 2.4).

The following discriminant dimensions were more related to the specific objective of each typology. For the typology T1, PC1, PC2, PC3 and PC4 were related to the most important livestock activity (i.e. contribution of each livestock type to the total tropical livestock units (TLU) represented by *cattleratio*, *chickenratio*, *pigratio* and *smallrumratio* respectively), thus distinguishing the farms by their dominant livestock type (Figure 2.2). The six resulting farm types are organized along a land and TLU gradient, from type 1 (larger farms) to type 6 (smaller farms). In addition to land and TLU, the farm types differed according their herd composition: large cattle herds for type 1 and type 2, mixed herds of cattle and small ruminants or pig for type 3, mostly pigs for type 4, small ruminant herds for type 5 and finally, mostly poultry for type 6 (Figure 2.2).

For the typology T2, the labour constraints for land preparation (*preplabrat*) and weeding (*weedlabrat*) determined the second discriminant dimension (PC2), while the legume features (experience, legume evaluation and cropped legume proportion represented by *legexp*, *legscore* and *legratio* respectively) only appeared correlated to PC3 or PC4. However, these two last dimensions were not useful to discriminate the surveyed farms, since the farm types tended to overlap in PC3 and PC4 (Figure 2.3). Therefore, while these were variables of interest (i.e. targeted in the T2-typology objective), no clear difference or trend across farm types was identified for the legume features in the multivariate results (Figure 2.3). The five resulting farm types were also organized along a land and TLU gradient, which was correlated with the income generated per year from cropping activities (*cropincome*) and the hired labour (*hiredcost*), ranging from type 1 (higher resource-endowed farms employing a large amount of external labour) to type 5 (resource-constrained farms, using almost only family labour). Furthermore, type 4 and type 5 were characterized by their most time-consuming cropping activity, weeding and soil preparation respectively (Figure 2.3).

For the typology T3, Lundazi, Chipata and Katete farms tended to primarily be distinguished according to a farm size, labour and income gradients (Figure 2.4). The number of the livestock units (*tlu*) remained an important discriminant dimension that was correlated to either PC1 or PC2 in the three districts

(Figure 2.4). Although the selection of the variables was made to differentiate the farmers according to their legume practices (*legratio*), this dimension appeared only in PC3 or PC5, explaining less than 12% of the variability surveyed. Moreover, similarly to T2, the farm types identified were not clearly distinguishable on these dimensions (data not shown here). Thus, besides the clear differences among farms in terms of their land size, labour and income (PC1), farms were primarily segregated by their source of income, i.e. cropping activities (*cropincratio*) vs. animal activities (*anlincratio*) (Figure 2.4, *offincome* not shown). In T3-Lundazi, T3-Chipata and T3-Katete, the resulting farm types were also organized along a resource-endowment gradient, from type 1 (higher resource-endowed farms) to type 6 (resource-constrained farms). Additionally, they were distinguished by their main source of income: i) for T3-Lundazi, large livestock sales for type 2, mostly crop products sales (low livestock sales) for types 1, 3, 4, and 6, and off-farm activities for type 5; ii) for T3-Chipata, crop revenues for type 3, livestock sales for type 2 and mixed revenues from crop sales and off-farm activities for type 1, 4 and 5; iii) for T3-Katete, crop revenues for types 3 and 5, mixed revenues from crop sales and off-farm activities for type 1, 2 and 4, and mixed revenues from livestock sales and off-farm activities for type 6 (Figure 2.4, *offincome* not shown).

The overlap of the typologies is presented in Figures 2.5 and 2.6. A strong overlap is indicated by a high percentage (and darker shading) in only one cell per row and column (Figures 2.5b and 2.6). The overlap between the presented typologies was not clear (Figures 2.5 and 2.6) despite the importance of farm size, labour and income in the first principle component (PC1) in all typologies. The best overlap was observed between the typology T2 and the typology T3 for the Chipata district (T3-Chipata). Moreover, the types 1 (i.e. farms with larger farm area, higher income and more labour used) overlapped between typologies: 69% of type 1 from T2 belonged to type 1 from T1 (Figure 2.5) and, 100 and 89% of the types 1 from Lundazi and Katete, respectively, belonged to type 1 from T2 (Figure 2.6). The majority of the unclassified farms (i.e. farms present in T1 but detected as outliers in T2 and T3) were related to the 'wealthier' types, type 1 and type 2 (Figures 2.5 and 2.6).

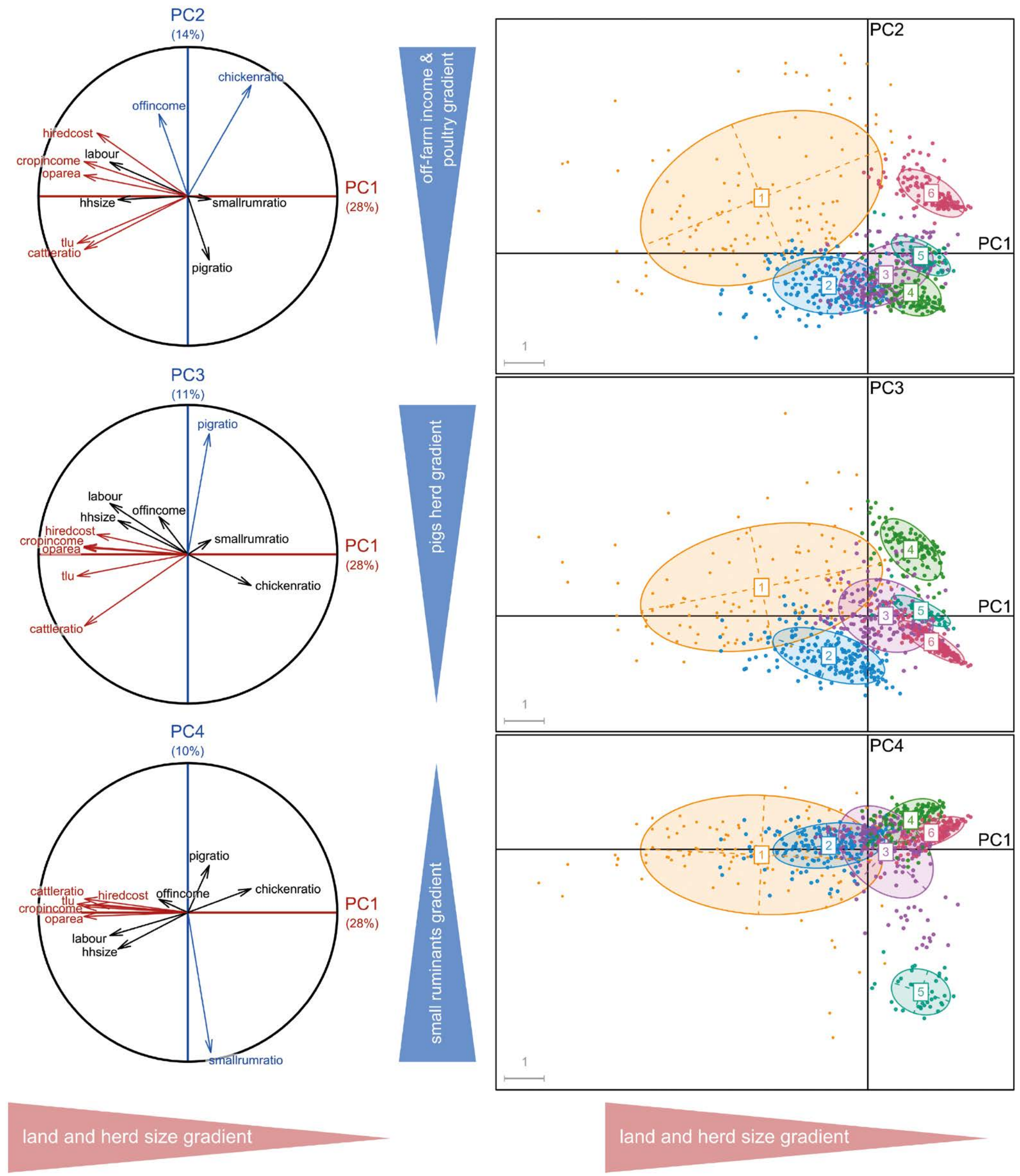

Figure 2.2 Typology 1: Representation of the six farm types of resulting from the Principal Component Analysis and clustering analysis on the planes defined by the first four principal components. The red colour variables are the most explanatory of the horizontal axis (PC1); those in blue are the most explanatory variables of vertical axes (PC2, PC3 and PC4), thus defining the gradients.

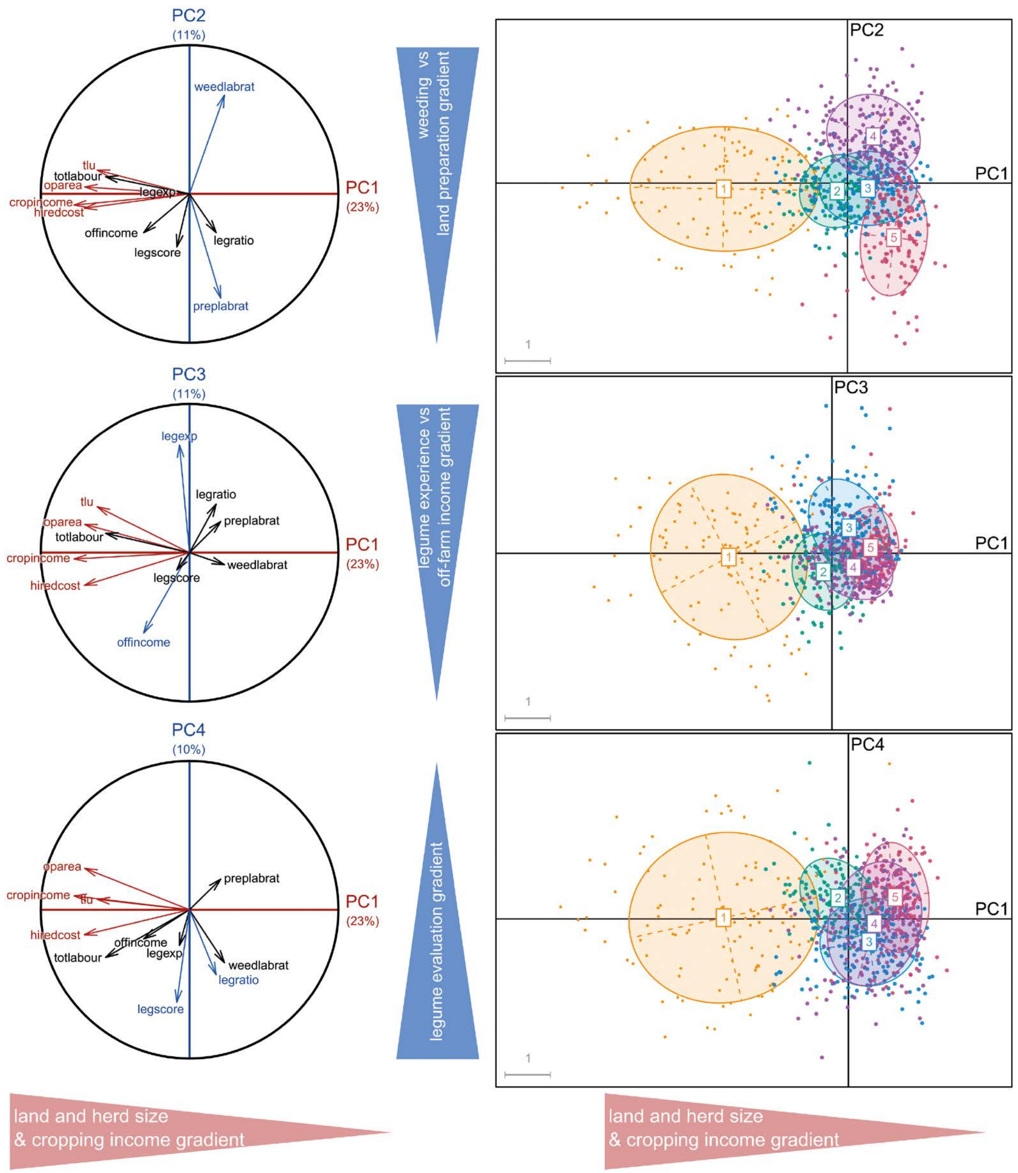

Figure 2.3 Typology 2: Representation of the five farm types of resulting from the Principal Component Analysis and clustering analysis on the planes defined by the first four principal components. The red colour variables are the most explanatory of the horizontal axis (PC1); those in blue are the most explanatory variables of vertical axes (PC2, PC3 and PC4), thus defining the gradients.

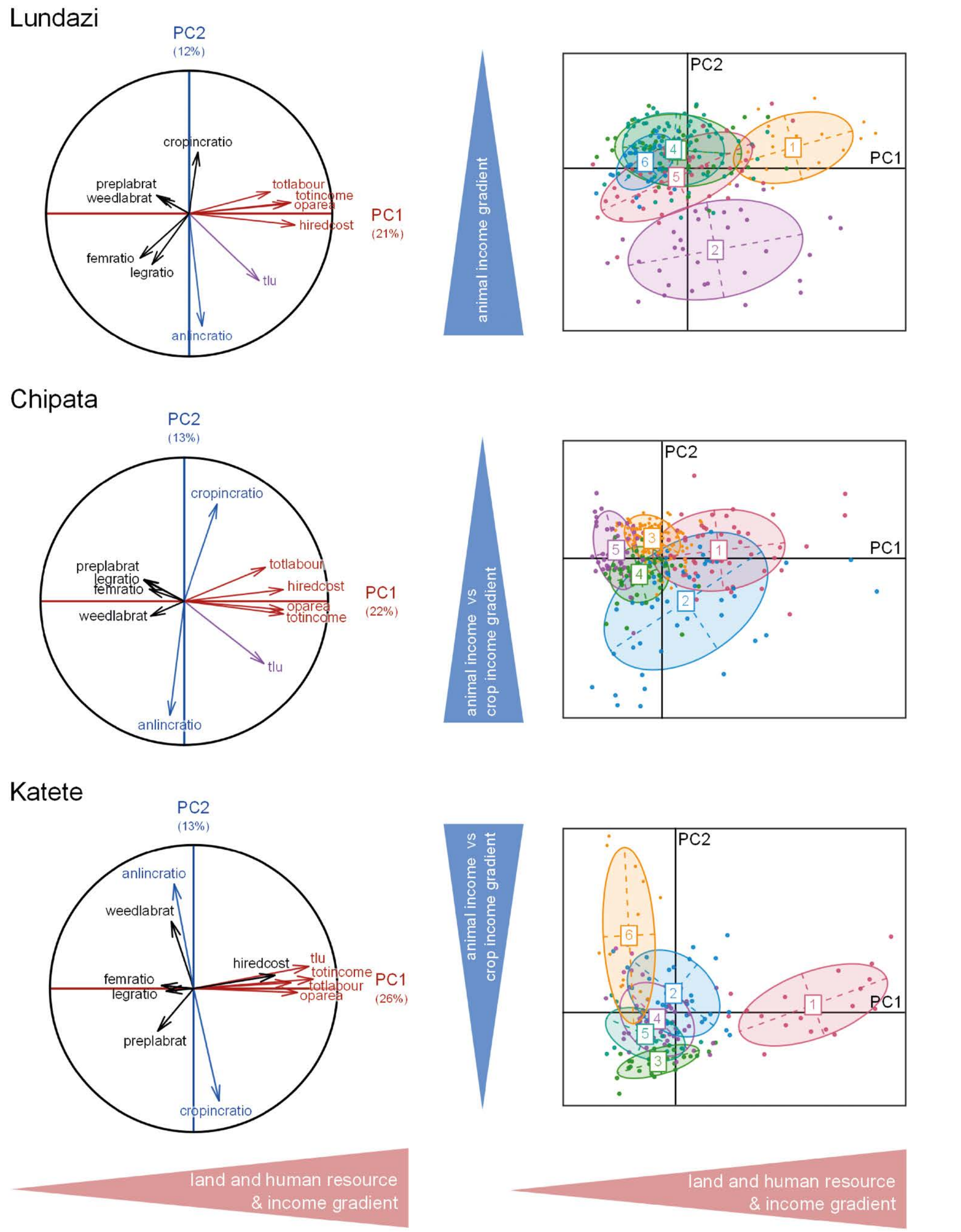

Figure 2.4 Typology 3: Representation of the farm types of resulting from the Principal Component Analysis and clustering analysis on the planes defined by the first four principal components, for the districts Lundazi, Chipata and Katete. The red coloured variables are the most explanatory of the horizontal axis (PC1); those in blue are the most explanatory variables of vertical axes (PC2) and those in violet are variables correlated with both PC1 and PC2.

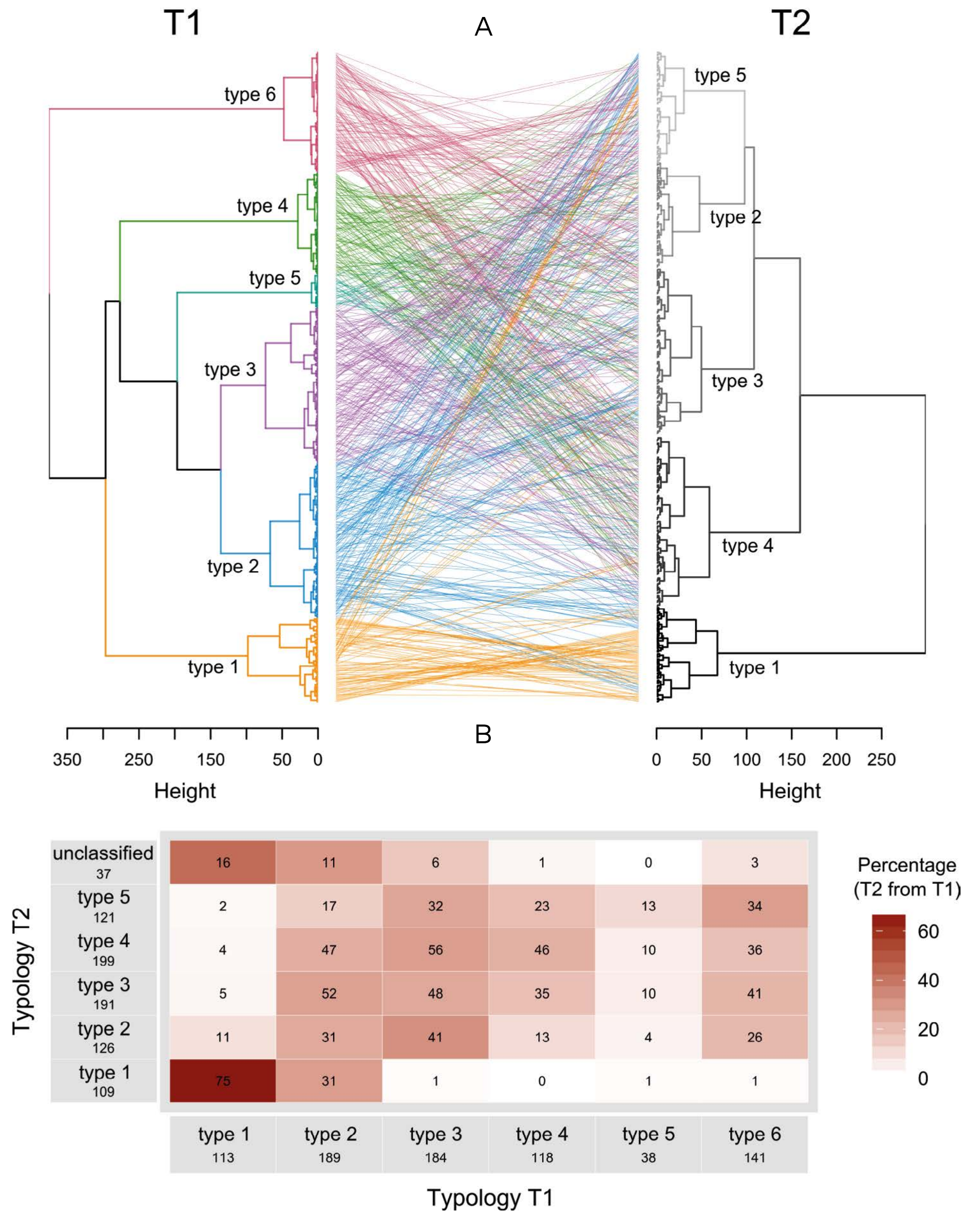

Figure 2.5 (a)Comparison of the two dendrograms from the resource-based typology (T1) and the crop-based typology (T2), and (b) cross-tabulation of numbers of farms of T1 allocated to different types of T2; the intensity of the red colouring indicates the percentage of overlap. The 'unclassified' farms are farms that were included in T1 but were detected as outliers for T2. Figure 2.6a illustrates the overlapping between T1 and T2, comparing the individual position each farm in the two dendrogram of the two typologies, while Figure 2.6b quantifies the percentage of overlap between the two typologies.

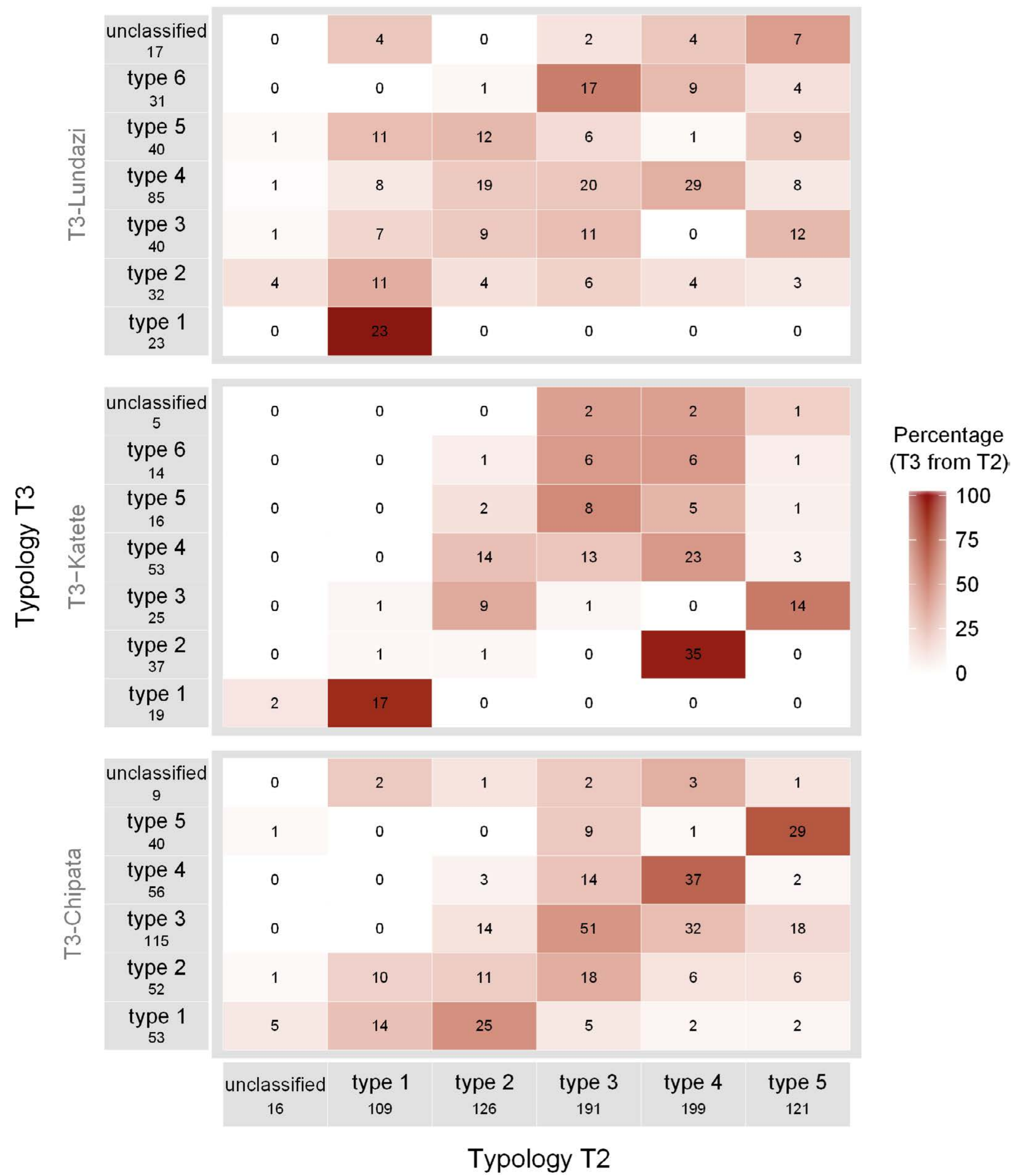

Figure 2.6 Cross-tabulations of numbers of farms of typology T2 allocated to different types of typologies for districts Lundazi (T3-Lundazi), Chipata (T3- Chipata) and Katete district (T3- Katete). The intensity of the red colouring indicates the percentage of overlap.

For the all the typologies (T1, T2, T3-Lundazi, T3-Chipata and T3-Katete), the main discriminating dimension was related to resource endowment: farm structure in terms of land area and/or animal numbers, labour use and income, which has been observed in many typology studies. In this case, the change in typology objective and the corresponding inclusion of variables from the dataset on legume integration (e.g. *legratio*) did not result in a clearer separation among farm types in T2 when compared to T1. The importance of farm structure variables in explaining the datasets' variability (Figures 2.2, 2.3 and 2.4) resulted in overlap among typologies regarding the larger, more well-endowed farms, that comprised ca. 10% of the farms, but for types representing medium- and resource-constrained farms the overlap between typologies was limited (Figures 2.5 and 2.6).

The difference between typologies T2 and T3 relate to a scale change, i.e. from province to district scale. Zooming in on a smaller scale allows amplification of the local diversity. Indeed, the range of variation could be different at provincial level (i.e. here three districts were merged) when compared to the district level (Table 2.1). Thus narrowing the study scale makes intra-district variability more visible, and potentially reveals new types leading to a segregation/splitting of one province-level type into several district-level types (Figure 2.7). The differences between typologies that arise from scale differences highlight the importance of scale definition when investigating out-scaling and up-scaling of target interventions.

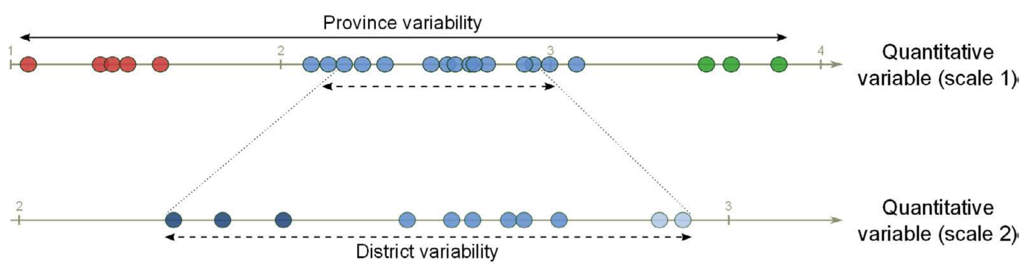

Figure 2.7 Theoretical example of a change of scale, from scale 1 to scale 2 (e.g. from province to district). Distribution of observations of a quantitative variable (e.g. farm area) at the province level (level 1) and at the district level (level 2). The different colours are associated with different values classes within the variable. Zooming in from scale 1 to scale 2, magnifies the variation within the district, potentially revealing new classes.

2.4 Methodological framework for typology construction

The proposed methodological framework (Figure 2.8) aims to integrate statistical and participatory methods for hypothesis-based typology construction using quantitative data, to create a typology that is not only statistically sound and reproducible but is also firmly embedded in the local socio-cultural, economic and biophysical context. From a heterogeneous population of farms to the grouping into coherent farm types, the step-wise structure of this typology construction framework comprises the following steps: i) precisely state the objective of the typology; ii) formulate a hypothesis on farming systems diversity; iii) design a sampling method for data collection; iv) select the variables characterizing the farm households; v) cluster the farm households using multivariate statistics; and vi) verify the typology result with the hypothesis and discuss the usability of the typology with (potential) typology users. This step-wise process can be repeated if the multivariate analysis results do not match the diversity of the targeted population as perceived by the typology users. (Figure 2.8).

Typology objectives, target population and expert panel

A farm typology is dependent on the project goals and the related research, innovation or development question (Köbrich, Rehman and Khan, 2003), which determine the typology objective. This will affect the delineation of the system under study, i.e. the target population size, in socio-institutional and geographical dimensions. The socio-institutional aspects that affect the size of the target population include criteria such as the type of entities involved (e.g., farms, rural households or individual farmers) and some initial cut-off criteria. These cut-off criteria can help in reducing the population size, such as a minimum or maximum structural size or the production orientation (e.g., food production, commercial and/or export-oriented; conventional or organic). The geographical dimension will affect the size of the target population by determining the spatial scale of the study, which in turn can be influenced by natural or administrative boundaries or by biophysical conditions such as suitability for farming. The scale at which the study is conducted can amplify or reduce the diversity that is encountered (cf. Figure 2.7).

Stakeholders (including farmers) with a good knowledge of the local conditions and the target population and its dynamics can inform the various steps of the typology development, forming an expert panel for consultation throughout the typology construction process. The composition of the panel can be related to the objective of the typology. Existing stakeholder selection techniques (e.g. Dossa *et al*., 2011; Mwijage *et al*., 2009) can be used for the identification and selection of panel experts. The group of experts can be split into a 'design panel' that is involved in the construction of the typology, and a 'validation panel' for

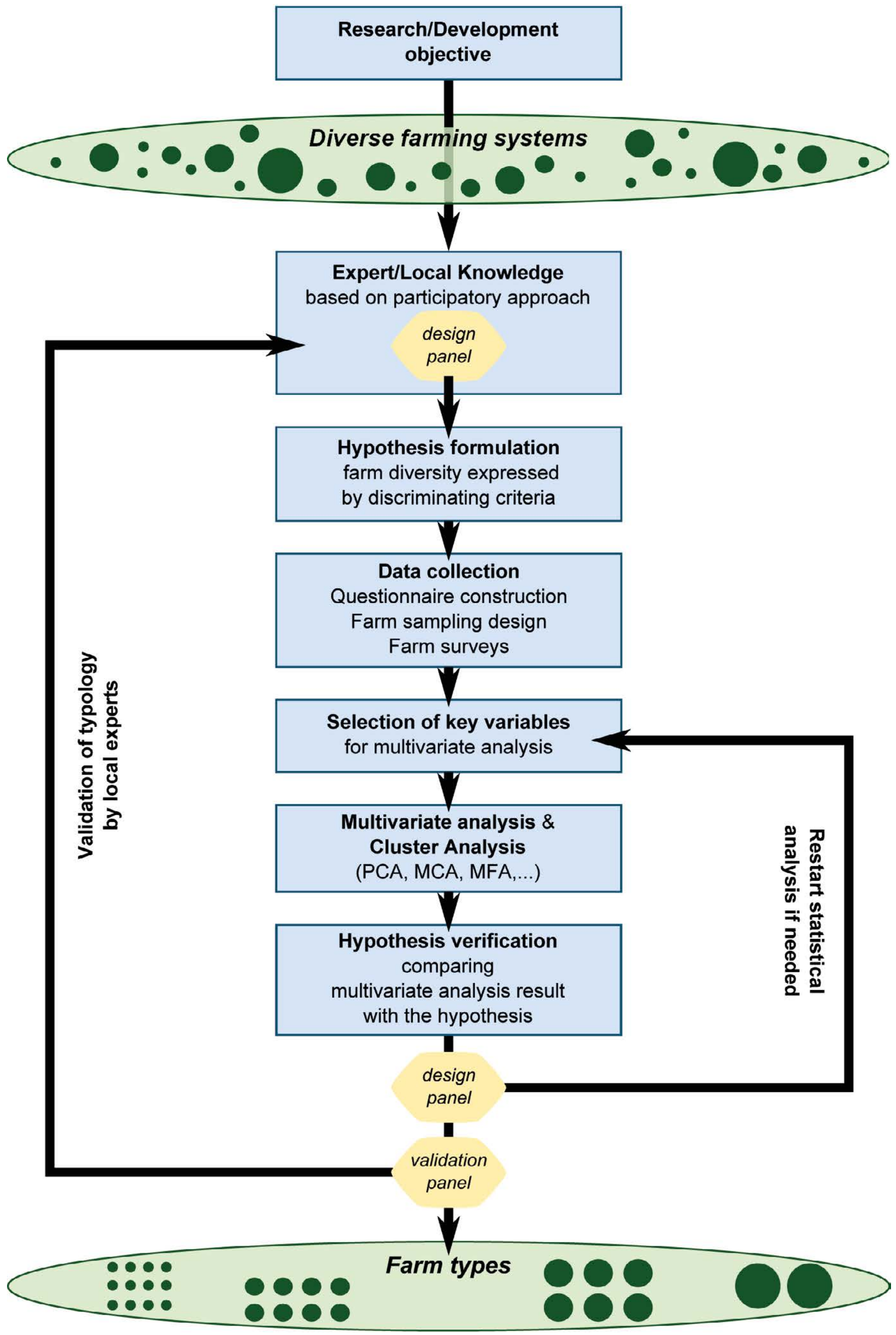

Figure 2.8 General framework of the typology process, where expert knowledge is combined with statistical techniques (PCA: Principal Component Analysis; MCA: Multiple Correspondence Analysis; MFA: Multiple Factorial Analysis).

independent validation of the result (cf. section 'Hypothesis verification and typology validation'). Finally, involving local stakeholders who are embedded in the target population may trigger a broader local involvement in the research process, facilitating data collection and generating more feedback and acceptance and usability of the results (Rey, 1989).

Hypothesis on typology structure

A multiplicity of typologies could describe the same faming environment depending on the typology objective and thus the selected criteria for typology development (Rey, 1989). In the proposed framework (Figure 2.8), the typology development is based on the formulation of a hypothesis on the diversity of the target population by the local experts, the design panel, in order to guide the selection of variables to be used in the multivariate statistical analysis. The hypothesis relates to the main features of local agriculture, stakeholder assumptions and theories on farm functioning and livelihood strategies in the local context, and on their interpretation of the relevant external forces and mechanisms that can differentiate farm households. Heterogeneity can emerge in response to very diverse socio-cultural, economic and biophysical drivers that can vary in significance within the studied region. In addition to the primary discriminatory features, the hypothesis can also make the following features explicit; the most prominent types of farms that are expected, their relative proportions, the most crucial differences between the farm types, the gradients along which the farms may be organized and possible relationships or correlations between specific farm characteristics. These perceptions and theories about the local diversity in rural livelihoods and farm enterprises are often present but are not always made explicit; the hypothesis formulation by the design panel is meant to make these explicit and intelligible to the external researchers. Hence, the design panel is expected to reflect on the drivers and features of the farm diversity encountered in the targeted population and reach a consensus on the main differentiating criteria and, ideally, have a preliminary inventory of the expected farm types.

An example of a hypothesis formulated by local experts could be that farms are distinguished by the size of the livestock herd, their reliance on external feeds and their proximity to livestock sale-yards; thus, there may be a gradient from large livestock herds, very reliant on external feeds, and close the sale-yards, to small herds, less reliant on external feeds further away from sale-yards. The discussions of the design panel are guided by the general typology objective. The hypothesis can further be informed by other participatory methods, previous studies in the area or by field observations. This allows for a wide range of information to be used for the hypothesis consolidation. Most of the information compiled in the formulated hypothesis is qualitative, but can also be informed by maps and spatial data in geographical information systems. The statistical analysis that follows will use quantitative features and boundaries of the farm entities in the study region.

Data collection, sampling and key variables selection

The creation of a database on the target population is an essential step in the typology construction based on quantitative methods. The farm sampling needs to capture the diversity of the target population (Pacini *et al.*, 2014). The size of the sample and the sampling method (Kumar, 2014) affect the proportion of farms belonging to each resulting farm type; for instance a very small farm type is likely to be absent in a reduced sample. Thus the sampling process, notably the choice of sample size, should be guided by the initial hypothesis.

The survey questionnaire needs to reflect the hypothesis formulated in the previous step, i.e. containing at least the main features and differentiation criteria listed by the design panel. However, the survey can be designed to capture the entire farming system (Tittonell *et al.*, 2010; Giller *et al.*, 2011), collecting information related to all its components (i.e. household/family, cropping system, livestock system), their interactions, and the interactions with the biophysical environment in which the farming system is located (e.g. environmental context, economic context, socio-cultural context). The anticipated analytical methods to be applied, especially the multivariate techniques, also guide decisions about the nature of data (e.g. categorical or continuous data) to collect.

Finally, the selection of key variables for the multivariate analysis is adapted to the typology objective following the previous step of exchanges with the expert panel and hypothesis formulation. Together researchers and the expert design panel select the key variables that correspond to the formulated hypothesis. These selected key variables constitute a sub-database of the collected data, which will be used for the multivariate analysis. Kostrowicki (1977) advised to favour integrative variables (i.e. combining several attributes) rather than elementary variables. The number of surveyed entities has to be larger than the number of key variables; a factor five is often advised (Hair *et al.*, 2010).

Multivariate statistics

Multivariate statistical analysis techniques are useful to identify explanatory variables (discriminating variables) and to group farms into homogeneous groups that represent farm types. A standard approach is to apply a data-reduction method on the selected set of variables (key variables) to derive a smaller set of non-correlated components or factors. Then clustering techniques are applied to the coordinates of the farms on these new axes. Candidate data-reduction techniques include: i) Principal Component Analysis for quantitative (continuous or discrete) variables [e.g. Tittonell *et al.*, 2010; Bidogeza *et al.*, 2009; Sanogo, de Ridder and van Keulen, 2010); ii) Multiple Correspondence Analysis for categorical variables (e.g. Kostrowicki and Tyszkiewicz, 1970); iii) Multiple Factorial Analysis for categorical variables organized in multi-table and multi-block data sets (e.g. Alary *et al.*, 2002); iv) Hill and Smith Analysis for mixed quantitative and qualitative variables (e.g. Rueff *et al.*, 2012); v) Multidimensional scaling to build a classification configuration in a specific dimension (e.g. Pacini *et al.*, 2014; Righi *et al.*, 2011); or vi) variable clustering to reduce qualitative and quantitative variables into a small set of (quantitative) "synthetic variables" used as input for the farm clustering (e.g. Kuentz-Simonet *et al.*, 2013). Although the number of key variables is reduced, the variability of the dataset is largely preserved. However, as a result of the multivariate analysis, not all the key variables selected will necessarily be retained as discriminating variables.

Subsequently, a classification method or clustering analysis (CA) can be applied on these components or factors to identify clusters that minimize variability within clusters and maximize differences between clusters. There are two methods of CA commonly used: i) Non-hierarchical clustering, i.e. a separation of observations/farms space into disjoint groups/types where the number of groups (k) is fixed; and ii) Hierarchical clustering, i.e. a stepwise aggregation of observations/farms space into disjoint groups/types (first each farm is a group all by itself, and then at each step, the two most similar groups are merged until only one group with all farms remains). The Agglomerative Hierarchical Clustering algorithm is often used in the typology construction process (e.g. Chopin, Blazy and Doré, 2015; Alary *et al.*, 2002; Blazy *et al.*, 2009, Pacini *et al.*, 2014; Sanogo *et al.*, 2010). The two clustering methods can be used together to combine the strengths of the two approaches (e.g. Kuivanen *et al.*, 2016a; Iraizoz, Gorton and Davidova, 2007; Michielsens *et al.*, 2002). When used in combination, hierarchical clustering is used to estimate the number of clusters, while non-hierarchical clustering is used to calculate the cluster centres. Some statistical techniques exist to support the choice of the number of clusters and to test the robustness of the cluster results, such as clustergrams, slip-samples or bootstrapping techniques (Hair *et al.*, 2010, Mucha, 2014; Schonlau, 2003). The "practical significance" of the cluster result has to be verified (Hair *et al.*, 2010). In practice, a limited number of farm types is often preferred, e.g. three to five for Giller *et al.* (2011), and six to fifteen for Perrot and Landais (1993).

Hypothesis verification and typology validation

The resulting farm types have to be conceptually meaningful, representative of and easily identifiable within the target population (Moreno-Perez, Arnalte-Alegre and Ortiz-Miranda, 2011). The farm types resulting from the multivariate and cluster analysis are thus compared with the initial hypothesis (cf. Section 2.2; Figure 2.8), by comparing the number of types defined, their characteristics and their relative proportions in the target population. The correlations among variables that have emerged from the multivariate analysis can also be checked with local experts. This has to be part of an iterative process where the results of the statistical analysis are compared with the reality of the target population in discussion with the expert panels (Figure 2.8). When involved in this process, local stakeholders can help in understanding the differences between the hypothesis and the results of the statistical analysis. In the case of results that deviate from the hypothesis, the multivariate and cluster analysis may need to be repeated using a different selection of variables, by examining outliers or the distributions of the selected variables. The discussion and feedback sessions with local stakeholders ('design panel' of experts) may need to be re-initiated until no new information emerges from the feedback sessions. Later, the driving effects of external conditions (such as biophysical and socio-economic features) on farming systems differentiation can be tested statistically analysing the relationships between the resulting farm types and external features variables.

Finally, when the design panel recognizes the farm types identified with the statistics analysis, an independent assessment of the typology results and its usability by potential users is desired (Figure 2.8). Preferably, to allow an independent verification of the constructed typology, this 'validation panel' should be independent of the design panel that formulated the hypothesis. The resulting typology is presented to the validation panel whose members are asked to compare it with their own knowledge on the local farming systems diversity. The objective of this last step is to, in hindsight, demonstrate that the simplified representation reflected in the typology is a reasonable representation of the target population and that the typology satisfies the project goals. Some criteria were proposed to support the validation process of the typology by the validation panel (Legendre, 2005 cited by Larouche, 2011): i) Clarity – farm types should be clearly defined and thus understandable by the local stakeholders (including the validation panel); ii) Coherence – examples of existing farms should be identifiable by the local experts for each farm type, and, any gradient highlighted during the hypothesis formulation should be recognizable in the typology results; iii) Exhaustiveness – most of the target population should be included in the resulting farm types; iv) Economy – the typology should include only the necessary number of farm types to represent most of the target population diversity; and, v) Utility and acceptability – the typology should be accepted and judged as useful by the stakeholders (especially by the validation panel), for instance by providing diagnostics on the target population like the production constraints per identified farm type.

Thus, eventually the typology construction has gone through two triangulation processes: expert triangulation (by design panel and validation panel) and methodological triangulation (using statistical analysis and participatory methods).

2.5 General discussion

Importance of the learning process

The hypothesis-based typology construction process constitutes a learning process for the stakeholders involved such as local experts, local policy makers and research for development (R4D) project leaders, and for the research team that develops the typology. For the local stakeholders, the process could lead to a more explicit articulation of the perceived (or theorised) diversity within the farming population and use of the constructed typology. The process involves an exchange of ideas and notions, and provides incentives to find consensus among different perspectives. Obviously, the resulting typology itself allows for reflection on the actual differences between farming households and on opportunities for farm development. By recognizing different farm types and the associated distributions of characteristics, typologies could also help farmers to identify development pathways through a comparison of their own farm household system with others (Where am I?), identifying successful tactics and strategies of other farm types (What can I change?) and their performances (What improvement can I expect?).

The research team not only gains a quantitative insight into the diversity and its distribution from the developed typology, but also obtains a detailed qualitative view on the target population, particularly if selected farms representing the identified farm types are studied in more detail. Indeed, the interactions with local experts and discussions about the interpretation of the typology could also provide insights into, for instance, socio-cultural dynamics and power relations within the farming population and local institutions, as well as other aspects not necessarily collected during the survey. For example, social mechanisms can become more visible to the researcher when the relationships between farm types are described during the discussions with the expert panels.

Farm/household dynamics

Farms are moving targets (Giller *et al.*, 2011), while typologies based on one-time measurements or data collection surveys provide only a snapshot of farm situations at a certain period of time (Kostrowicki, 1977). Due to farm dynamics, these typologies could become obsolete and hence it is preferable to regularly update typologies (Valbuena *et al.*, 2015; Landais, 1988).

However, it has been argued that typologies based on participatory approaches tend to be more stable in time (Landais, 1988), because they are more qualitative and therefore could also integrate the local background and accumulated experience from the local participants. Consequently, the resulting qualitative types change less over time, although individual farms may change from one farm type to another (Perrot, Landais and Pierret, 1995; Alary *et al.*, 2002). Thus, the framework presented here would allow combining the longer-term (and more qualitative) vision of the local diversity from the local stakeholders including the general observed trend into the hypothesis formulation, and the shorter-term situation of individual households.

Typologies as social constructs

It is important to recognize that typology construction is a social process, and therefore that typologies are social constructs. The perspectives and biases of the various stakeholders in the typology construction process, including methodological decision-making by the research team (such as the selection of the key variables, principal component construction and interpretation, etc.) shape the resulting typologies, and subsequently their usability in research and policy making. Consequently, participatory typology construction may be considered as an outcome of negotiation processes between different stakeholders aiming to reach consensus on the interpretation of heterogeneity within the smallholder farming population (Leeuwis, 2000). To support these negotiation processes several pre-defined and widely used criteria can be applied, such as the Kaiser criterion. The consensus-oriented hypothesis formulation described here is also a way to mitigate the predominance of (the more powerful) individual stakeholders in shaping the typology constructing process. Multiple consultations, feedbacks to the local stakeholders and the typology 'validation' by the independent assessors further limit this predominance of more powerful stakeholder stakeholders.

Typology versus simpler farm classification

Taking into account multiple features of the farm household systems, typologies facilitate the comparison of these complex systems within a multi–dimensional space (Jollivet, 1965). However, with multivariate analysis, the underlying structure of the data defines the ranking of dimensions in terms of their power to explain variability. Therefore, as shown previously (cf. Section 'Results and discussion on the contrasting typologies'), there is no guarantee that the multivariate analysis will highlight one specific dimension targeted by the researcher or the intervention project. Thus, if the goal is simply to classify farms based on one or two dimensions, a simpler classification based only on one or two variables may suffice to define useful farm classes for the intervention project. For example, an intervention project focused on supporting new legume growers, could classify farm(er)s on their legume cultivated area and their years of experience with legume cultivation only. In that case, we would not use the term farm typology but rather farm classification.

Farm types and individual farmers

Farm typologies are groupings based on some selected criteria and the farm types tend to be homogeneous in these criteria, with some intra-group variability. Thus, typologies are useful for gathering farmers for discussion such that one would have groups of farmers who manage their farms similarly, have similar general strategies, or face similar constraints and have comparable opportunities. This is how typologies can be especially helpful in targeting interventions to specific farm types. However, individual farm differences remain; criteria that were not included in the typology and also individual farmer characteristics, such as values, culture, background or personal goals and projects can account for the observed individual farm differences. Thus, when interacting with individual farmers, much more farm-specific, social (household and community) and personal features can arise, for example their risk aversion or other hidden (non-surveyed) issues that would influence their adoption of novel interventions. This highlights the intra-type heterogeneity and also exposes the potential pitfalls when targeting interventions to be adopted by farmers.

2.6 Conclusion

Agricultural (research for) development projects that evaluate or promote specific agricultural practices and technologies usually provide a particular set of interventions, for instance oriented towards soil conservation, improvement of cropping systems or animal husbandry. The focus and aims of such projects shape also the differentiation of the project's target population into farm types that are often used for targeting interventions. In addition, a project's specific impact and out-scaling objectives influence the number of farmers targeted and the spatial scale at which the interventions need to be disseminated, thus influencing the farmer selection strategy. Constructing farm typologies can help to get a better handle on the existing heterogeneity within a targeted farming population. However, the methodological decisions on data collection, variable selection, data-reduction and clustering can bear a large impact on the typology construction process and its results. We argue that the typology construction should therefore be guided by a hypothesis on the diversity and distribution of the targeted population based both on the demands of the project and on prior knowledge of the study area. This will affect the farming household selection strategy, the data that will be collected and the statistical methods applied.

We combined hypothesis-based research, context specificities and methodological issues into a new framework for typology construction. This framework incorporates different triangulation processes to enhance the quality of typology results. First, a methodological triangulation process supports the fusion of i) 'snapshot' information from household surveys with ii) long-term qualitative knowledge derived from the accumulated experience of experts. This fusion results in the construction of a contextualized quantitative typology, which provides ample opportunities for exchange of knowledge between experts (including farmers) and researchers. Second, an expert triangulation process involving the 'design panel' and the 'validation panel', results in the reduced influence of individual subjectivity. As shown in the Zambian illustration, the typology results were highly sensitive to the typology objective and the corresponding selection of key variables, and scale of the study. Changing from one set of variables to another or, from one scale to another, resulted in the surveyed farms shifting between types (Figures 2.5 and 2.6). We have thus highlighted the importance of having a well-defined (and imbedded in local knowledge) typology objective and hypothesis at the beginning of the process. Taking into account both triangulation processes in the presented framework, we conclude that the framework facilitates a solid typology construction that provides a good basis for further evaluation of entry points for system innovation, exploration of trade-offs and synergies between multiple (farmer) objectives and to inform decisions on improvements in farm performance.

Beans on sale at Chipata market in the Eastern Province of Zambia in March 2014.
Photo: Mirja Michalscheck. ▶

Chapter 3
Exploring options for sustainable intensification through legume integration in different farm types in Eastern Zambia

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◀ Legume growing up a maize stalk. Photo: Mirja Michalscheck

TL:DR

- We found the following types:
  - L-LEGU: Low resource endowed, most labour for land preparation, legume growers;
  - L-WEED: Low resource endowed, most labour for weeding, few legumes grown;
  - M-LEGU: Medium resource endowed, legume growers, highest relative animal income;
  - MH-OFI: Medium to high resource endowed, highest off-farm income;
  - H-LVST: High resource endowed, high crop and animal income.

- We tested the following interventions:
  - maize–cowpea intercrop,
  - sole soybean crop,
  - sole cowpea crop,
  - maize after cowpea and
  - maize after soybean.

- Sole legume crops like soybeans were found beneficial (i.e. higher profit, organic matter added to the soil and lower labour requirement) to L-LEGU, MH-OFI and H-LVST types, whereas L-WEED and M-LEGU types benefitted more from sole cowpea.

- For types L-WEED, M-LEGU and MH-OFI, including maize after the legume crop was found to be beneficial.

- Only the MH-OFI type was shown to have some benefit from an intercrop of maize and cowpea

3.1 Introduction

In Zambia maize is the main staple food crop and, with a share of 52% in the daily calorie intake of the local population, it is critical for ensuring the national food security (FAOSTAT, 2013). Of the total maize consumed in Zambia, smallholder farmers produce 80% in rain-fed systems under low soil fertility, frequent drought and with a limited use of high yielding varieties or inorganic fertiliser (Sitko *et al*., 2011). In eastern Zambia, the livelihoods of smallholder farmers depend largely on maize-legume mixed systems characterised by low productivity, extreme poverty and environmental degradation (Sitko *et al*., 2011). Thus, there seems to be a great need for sustainable intensification of these farming systems, for instance through promoting best practices in maize–legume integration. Maize–legume cropping provides protein-rich food for humans, residues for animal feed, composting and soil amendments and nitrogen inputs through symbiotic fixation by the legume. Sustainable intensification of farming systems can take place through changes in resource use and allocation that increase farm productivity while reducing pressure on local ecosystems and safeguarding social relations. According to Pretty *et al*. (2011), this entails the efficient use of all inputs to produce more outputs while reducing damage to the environment and building a resilient natural capital from which environmental services can be obtained. Sustainable intensification results from the application of technological and socio-economic approaches that may be categorised into genetic, ecological and socio-economic intensification (The Montpellier Panel, 2013).

Smallholder farming systems are often highly diverse in terms of biophysical and socio-economic characteristics. The diversity among systems stems *inter alia* from differences in soil fertility, in farmers' livelihood aspirations and the availability of resources such as land, labour as well as financial assets. Hence, instead of providing blanket recommendations for smallholder farmers, recognising and responding to the variability in local farm characteristics can lead to more appropriate, targeted and effective (design) recommendations to achieve improvements in agricultural production (Ojiem *et al*., 2006; Tittonell *et al*., 2010; Chikowo *et al*., 2014). Farm typologies aim at meaningful groupings of farms into subsets, homogenous according to specific criteria (Anderson *et al*., 2007; Alvarez *et al*., 2014; Alvarez *et al*., 2018), which can be used for technology targeting. Creating these typologies attempts to reach a useful compromise between analysing every single farm and assuming a broad category such as 'smallholders in general' based on average characteristics.

The main objective of this study was to perform an ex-ante evaluation of farm-type specific interventions for sustainable intensification and innovation at the farm level. Subsidiary objectives were to: (i) characterise the diversity of farming systems within the action sites in terms of resource endowment and legume cultivation practices; (ii) diagnose the systems in terms of productive, environmental and economic performance; (iii) explore trade-offs and synergies among various farm performance indicators across farm types; and (iv) identify potential points of improvement based on farm interviews and model explorations.

3.2 Methodology

A baseline survey was conducted in 2011/2012 in Eastern Zambia (Chipata, Katete and Lundazi districts) to obtain an initial description of the local farming systems and their diversity, and to derive a statistical farm typology. The resulting typology allowed selection of representative farms per type for the detailed characterisation (DC) survey. The DC survey, conducted during June 2014, provided the basis for a complete farming system diagnosis and an exploration of innovations using the whole-farm model FarmDESIGN. The exploration with the computer model yielded suggestions for system redesign, aiming at an improvement in the economic, social and environmental performance as compared to the current farm situation.

Typology

The farm types for this research were generated by two multivariate analyses, a principal component analysis (PCA) and a hierarchical clustering analysis (performed with the statistical software R, package ade4) on the surveyed baseline farms (n = 746). An expert consultation served to develop a hypothesis on important farm characteristics to use to distinguish between farm types: '*farms differ in terms of their farming resources (land and labour) and their current application of integration of grain legumes*'. This hypothesis was used to support the selection of variables for PCA: variables related to farm structure (operated area, tropical livestock units), to labour resource and constraints (total labour inputs, cost of hiring labour, proportion of total labour input used for land preparation and for weeding), to income source (crop, livestock and off-farm incomes) and to legume[2] practices (proportion of total operated area cultivated with legumes, years of experience in growing legumes and farmer's legume evaluation) were used. The hierarchical cluster analysis allowed classification of the farms into different farm types. The typology method was based on the guidelines set out in Alvarez *et al.* (2014; 2018).

2. Legumes included common bean, soybean, pigeon pea, groundnut and cowpea.

Detailed characterisation

To perform the DC, for each farm type, a representative farm was selected from each of the three districts (Chipata, Katete and Lundazi) in the Eastern Province of Zambia (n = 15). The DC survey tool was developed for the data needs of the FarmDESIGN model. The captured data was used for the parameterisation of the model. The DC was complemented by secondary data (results of trials conducted at Msekera Research station in Chipata, project reports and external literature).

Model analysis

FarmDESIGN is a bio-economic static model, capturing structural as well as functional farm characteristics (Groot *et al.*, 2012). It uses field crop information (e.g. plot sizes, crop types, intercrops and crop products) and cropping management practices such as manure, inorganic fertiliser, and pesticide use. The model also uses information on livestock (types, numbers and products) and on livestock management practices (e.g. animal feeding, livestock allotment, manure storage and herd replacement strategy). FarmDESIGN further assesses the destinations of crop and animal products such as household consumption, market sales or incorporation of residues into the fields. Also, soil and climate characteristics are integrated in the model. The FarmDESIGN model hence captures biophysical and economic features as well as management aspects of the particular farming system.

Based on these inputs, FarmDESIGN determines detailed nutrient cycles and annual feed balances, soil organic matter status, operating profit and labour balances. Beyond displaying the current farm situation, FarmDESIGN allows the exploration and evaluation of the impacts of different management decisions, changes in input use and production priorities. Based on available resources, the model is given a delimited room to reallocate these resources aiming towards defined farm objectives (desired outputs). The multi-objective optimisation algorithms generate diverse sets of alternative farm configurations that represent windows of opportunities or solution spaces for the case study farm (Groot and Rossing, 2011). The model aims to find alternative farm configurations using different decision variables to find configurations that achieve the objectives and that are within the constraints that have been set.

In this study, the decision variables used were the areas of the currently grown crops and five new 'intervention crops' suggested by project partners: (1) maize–cowpea intercrop, (2) sole soybean crop, (3) sole cowpea crop, (4) maize after cowpea and (5) maize after soybean. The explorations used three objectives: (i) to maximise farm operating profit, (ii) to maximise the organic matter added to the soil, and (iii) to minimise the farm labour requirements. The ranges of non-maize crops were restricted between 0 and 70% of the current total area and the range of maize and maize intercrops between 0 and 100% of the current total area. As the total farm area remains unchanged, a reduction in area of one or more of the currently grown crops will be reflected by an increase in area of a crop that is more favourable in terms of achieving the objectives. Constraints were set on the total farm area and the ruminant feed balance (animals must always be sufficiently fed in all configurations). The frontier of the resulting graphical solution cloud represents the possible Pareto-optimal farming systems alternatives according to the model and makes the trade-offs and synergies between objectives visible and able to be evaluated.

From the 15 farms surveyed in the DC, one farm of each type was chosen, based on its representativeness to its type, to be used for the final model analysis; one farm from Chipata and two farms each from Katete and Lundazi districts.

The information derived from the modelling is important in guiding discussions between farmers and stakeholders towards the selection of farm designs that are likely to be adopted by target farmers. The systems approach allows assessing the combined effects of changes in farm configuration on all other system components. Revealing the impacts of these system component changes provides information as to their suitability for that specific farm and for the type they represent.

3.3 Results

Typology

The local farming systems were grouped into five farm types mainly according to their resource endowment, their income source and their labour constraints (Table 3.1).

Type L-LEGU: Low resource endowed, most labour for land preparation, legume growers

L-LEGU farms tend to have the least cultivated land area and the lowest number of tropical livestock units (TLUs) with on average only one head of cattle and one goat (Table 3.1). On average, this farm type has the lowest share of farmers growing cash crops (62%) and the highest proportion of households reporting food insecurity (35%). L-LEGU farmers tend to cultivate a relatively large proportion of their fields with legumes and due to the low number of cattle available for draft power, spend the most labour on land preparation. They tend to spend the least proportion of labour on weeding compared to all types, probably due to their highest cost per hectare of herbicides.

Type L-WEED: Low resource endowed, most labour for weeding, few legumes grown

L-WEED farms tend to be relatively small in family size, cultivated land area and animal numbers (Table 3.1). L-LEGU and L-WEED types are quite similar in household size, operated area, crop diversity, per head income and total labour inputs, but a striking difference can be observed in their labour allocation. While L-LEGU farmers tend to spend most labour on land preparation, L-WEED farmers allocate the least labour to it and more to weeding. This might be associated with a higher number of cattle owned by L-WEED farms, which can assist with land preparation. Among all farm types, L-WEED farmers spend the largest share of labour on weeding and the smallest share on land preparation. More weeding labour was associated to low herbicide costs. Farmers of this type tend to be more food insecure than other farm types (except L-LEGU). On average, L-WEED farmers assign the least area of land to the cultivation of legumes.

Type M-LEGU: Medium resource endowed, legume growers, highest relative animal income

M-LEGU farms tend to have a medium farm and family size, intermediary animal numbers as well as an intermediary income compared to the other farm types (Table 3.1). On average this type cultivates the greatest share of their land with legumes. They tend to have long term experience in growing legumes, and this farm type could potentially provide useful information about farmers' reasons for adopting legumes, about best practices and how to overcome constraints reported by other types of farmers. They have the highest total labour inputs per hectare (185 person-days ha^{-1}).

Type MH-OFI: Medium to high resource endowed, highest off-farm income

MH-OFI farms tend to have, by far, the highest off-farm income. Whilst having on average a relatively large family size, farm area, animal number, crop diversity and a high food security, this farm type has the lowest shares of crop and animal incomes among all farm types (Table 3.1). Despite the small share of animal income compared to total income, the animal income per TLU is the second largest among all types indicating a large share of the TLU sales. MH-OFI farms are inclined to allocate relatively little labour to land preparation, which is possibly associated with the high number of cattle (on average four per farm) available for traction.

Table 3.1 Average characteristics per farm type for rain-fed smallholder systems in the Eastern Province of Zambia. The coding of the farm types is explained in the text.

Farm Types [3]	L-LEGU	L-WEED	M-LEGU	MH-OFI	H-LVST
Household Characteristics					
Number of people in household	6	6	7	8	9
Land use					
Cultivated land area (ha)	2.8	2.9	3.4	5.9	14
No. of crops grown	3	3	4	4	5
% of farmers growing cash crop(s)	62	70	72	74	82
Livestock					
Number of Cattle	1	2	2	4	13
Number of Goats	1	1	2	2	4
Number of Sheep	0	0	0	0	1
Number of Pigs	2	3	3	4	6
Number of Chicken	9	7	12	17	16
Tropical Livestock Units (TLU)	1	1.6	2.4	4.1	10.7
Animal Income per TLU (US$[4])	20.3	17.7	25.2	24.4	22.3
Food Security					
% of farms facing food shortage throughout the year or occasionally	35	29	25	17	8
Residue Use					
% of all residues used as green manure	52	58	52	57	57
% of all residues fed to livestock	23	21	24	20	24
Income sources and amounts					
Off-farm income as % of total income	32	26	23	44	8
Crop income as % of total income	64	69	70	53	87
Animal income as % of total income	4	5	7	3	5
Total revenues (US$[1])	508	567	865	3339	4762
Revenues per hh. member (US$[4])	83.0	89.9	128.9	428.2	555.7
Herbicide costs per hectare (US$[4])	0.68	0.13	0.17	0.16	0.45

Table 3.1 Continuation

Farm Types [3]	L-LEGU	L-WEED	M-LEGU	MH-OFI	H-LVST
Labour allocation					
Total labour (person-days year^{-1})	334	334	637	774	1031
Labour days per hectare	119	115	185	131	73
Labour for land preparation (%)	32	11	15	13	15
Labour for weeding (%)	24	46	34	29	27
Labour for harvesting (%)	29	31	34	36	36
Labour for shelling & threshing (%)	15	12	17	22	23
Legume related information					
% of total area cultivated to legumes	24	14	27	15	15
Years of experience growing legumes	4.5	3.9	8.7	4.7	8.9

3. L-LEGU: Low resource endowed, most labour for land preparation, legume growers; L-WEED: Low resource endowed, most labour for weeding, few legumes grown; M-LEGU: Medium resource endowed, legume growers, highest relative animal income; MH-OFI: Medium to high resource endowed, highest off-farm income; H-LVST: High resource endowed, high crop and animal income.
4. 1 US$ = 5115 ZMK as at 31 December 2011. (www.xe.com) ZMK is an obsolete currency since 1 January 2013. New currency is ZMW.

Type H-LVST: High resource endowed, high crop and animal income

H-LVST farms tend to have the highest overall revenues, attributable to their significantly higher resource endowment in terms of operated area as well as TLUs. The numbers of animals are the highest among all farm types (Table 3.1). H-LVST farms also have on average the largest share of farmers growing cash crops. They allocate more labour than other types to harvesting and shelling and threshing, indicating greater efforts in collecting and processing, adding market value to their farm products. This farm type has the greatest number of family members who contribute most of their labour to on-farm activities (concluded from comparatively low off-farm income). They are inclined to have the lowest amount of labour inputs per hectare (on average 2.5 times less than farm type M-LEGU), quite possibly due to their highest absolute expenses on herbicides when compared to other farm types. The high crop diversity makes farm households of this type resilient against climate and market price fluctuations, shown by the lowest share of households with food shortages. H-LVST farms tend to have the most experience in growing legumes among all farm types, but they allocate a relatively low share of their cultivated area to legumes.

In conclusion, from the types L-LEGU to H-LVST, an increasing gradient of revenues per household member, TLUs, land area and total labour is highlighted while food shortage decreases (Table 3.1). L-LEGU and M-LEGU farm types crop more legumes, and MH-OFI and H-LVST farm types have respectively an off-farm income generation or livestock activities orientation.

Model-based exploration

Model-based explorations were performed for five representative farms selected from each farm type (based on average features presented in Table 3.1). The scenario used entailed variable areas of the five new 'intervention crops'. The results from the explorations are presented below. The current situation of each farm is presented in Table 3.2. The results of the explorations (i.e. the solution space, with each dot representing an alternative farm configuration) are visualised in Figures 3.1 and 3.2.

Trade-offs were identified between increasing operating profit and the other two objectives (increasing organic matter inputs and reducing labour requirements) for the five farm types, with only a few exceptions. In general, increasing the operating profit would require an increase in labour input (except for farm L-WEED; Figure 3.1c), and farm configurations with larger amounts of organic matter inputs into the soil would have lower operating profit (except for farm H-LVST; Figure 3.1a). There was a synergy between increasing organic matter inputs and reducing the labour requirements for farm L-LEGU and M-LEGU (Figure 3.1b).

H-LVST farm had the highest operating profit for all alternative configurations and the M-LEGU farm reaches the highest organic matter added to the soil (Figure 3.1a). The distance between the alternative farm configuration points and the current situation (horizontally or vertically) indicates the magnitude of the increase or decrease that can be reached in each objective. It can be seen that the L-WEED farm had relatively little room for increases in operating profit, yet has a large range for improvement in soil organic matter inputs. The result of this small range in operating profit probably stems from the fact that this farm's yields for maize are low (using local maize variety with low yield and possibly poor management) and hence the predicted yields used for intervention crops were consequently low too. The reason that the points for the H-LVST farm have a different shape to that of the other types is due to the fact that this farm with its large area (23 ha) has a larger room to manoeuvre to find different configurations and thus the trade-offs between operating profit and the other objectives were less pronounced than for the smaller farms. For each alternative configuration, it is also possible to examine the corresponding changes in crop areas, i.e. decision variables, according to the three objectives (Figure 3.2). Figure 3.2a–f shows the maize area and the sum of the areas of other currently grown non-maize crops respectively. Almost all alternative configurations for the five farm types had less maize area than are currently allocated to that crop; thus it seems to be more advantageous in terms of profit, organic matter additions and labour reduction to replace (at least partly) the currently grown maize crop with either a currently grown non-maize crop or a new 'intervention crop'. In the Figure 3.2a–c, it can be seen for the L-LEGU and H-LVST farms that the model chose to replace the entire current maize crop area for another crop; all the points for these two types are at or near zero.

From Figure 3.2g–u it is apparent that the model chose to create alternative configurations with specific intervention crops for specific farm types. This indicates the suitability of that intervention for that type showing the potential adoption of these interventions under the constraints faced by the farm. Some intervention crops, such as the maize and cowpea intercrop and the maize after soybean crop, were only chosen for one type, the MH-OFI. The figure also shows that in some cases only one intervention crop was chosen for a type: the sole soybean for the L-LEGU type and maize after cowpea for the M-LEGU type. For the L-WEED type, the model chose the sole cowpea intervention in a greater amount, although the absolute area was relatively small. In addition, the model also chose to allocate land to maize after cowpea for the L-WEED type; thus for this type the combination of cowpeas in rotation with maize could prove to be a successful intervention. The MH-OFI type was allocated area by the model to almost all of the tested interventions. The increases of sole soybean area and maize and cowpea intercrop area for this type correspond with the trade-off trend of increases in the organic matter added and decreases in operating profit (Figures 3.2g–h and m–n). For the H-LVST type the model allocates relatively little land to intervention crops; the only intervention crop chosen by the model is sole soybean (Figure 3.2g–u) but the area is quite small (just over 1 ha out of the 23 ha that are available).

Finally, sole soybean should be suitable for all types except M-LEGU, sole cowpea for all types except L-LEGU. A maize and cowpea intercrop is suited to MH-OFI, but only for small areas as for larger areas the added labour and hence lower profit would make this intervention less attractive. Maize after soybean would be a better intervention for MH-OFI farms, as there are synergies with labour required and profit. Maize after cowpea would be suitable for M-LEGU, MH-OFI and L-WEED types.

Table 3.2 The current situation of the five representative rain-fed smallholder systems in the Eastern Province of Zambia, chosen as representative of their type for exploration in FarmDESIGN. The coding of the farm types is explained in the text.

Farm Types[5]	L-LEGU	L-WEED	M-LEGU	MH-OFI	H-LVST
Farm area (ha)	3.2	2.0	6.7	13.4	23.0
Crops currently grown	Maize Groundnut Cowpeas Tobacco Pumpkin	Maize Groundnut Sunflower Cotton Sw. Potato Sugarcane Pumpkin Vegetables	Maize Groundnut Sunflower Soybean Sw. Potato Cassava	Maize Groundnut Sunflower Pumpkin Cowpea Vegetables	Maize Groundnut Sunflower Cotton Vegetables
Animals currently owned	Pigs Chickens	Cattle Pigs	Cattle Chickens Goats	Cattle Chickens Goats Sheep Pigs Ducks	Cattle Chickens Goats Pigs Doves
Operating Profit (US$[6] year^{-1})	1 299	101	939	2 625	5 604
Organic Matter added (kg ha^{-1} year^{-1})	1 229	1 147	1 451	1 222	710
Labour Req. (hours year^{-1})[7]	0	50	3 027	5 503	360

5. L-LEGU: Low resource endowed, most labour for land preparation, legume growers; L-WEED: Low resource endowed, most labour for weeding, few legumes grown; M-LEGU: Medium resource endowed, legume growers, highest relative animal income; MH-OFI: Medium to high resource endowed, highest off-farm income; H-LVST: High resource endowed, high crop and animal income.
6. 1US$ = 6.259 ZMW as at 1 July 2014 (www.xe.com)
7. Additional hours over and above family labour required to manage crops and animals, represents labour hours that will have to be hired.

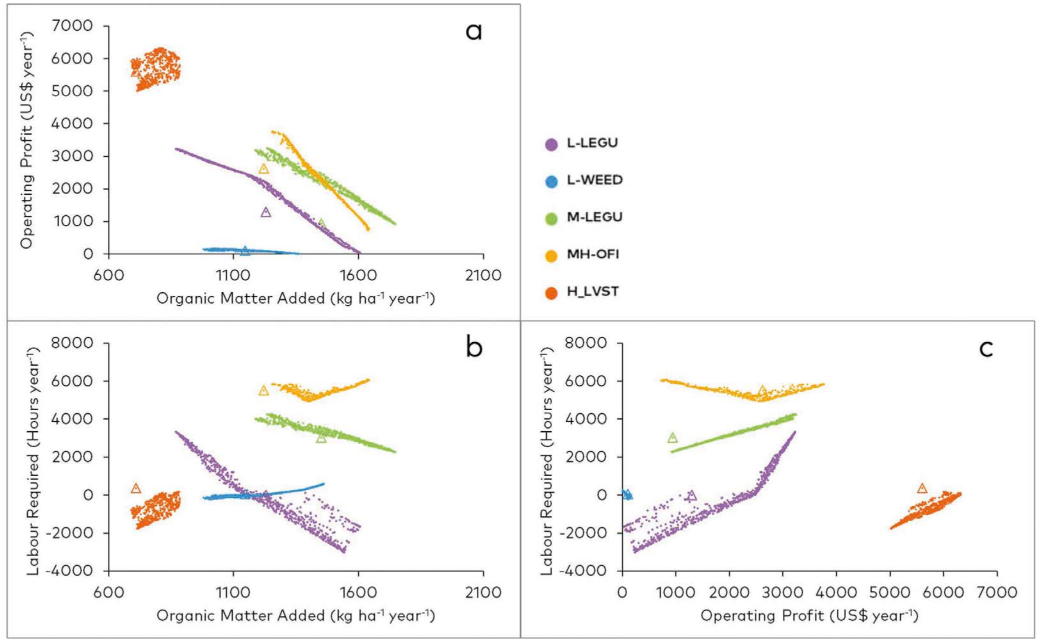
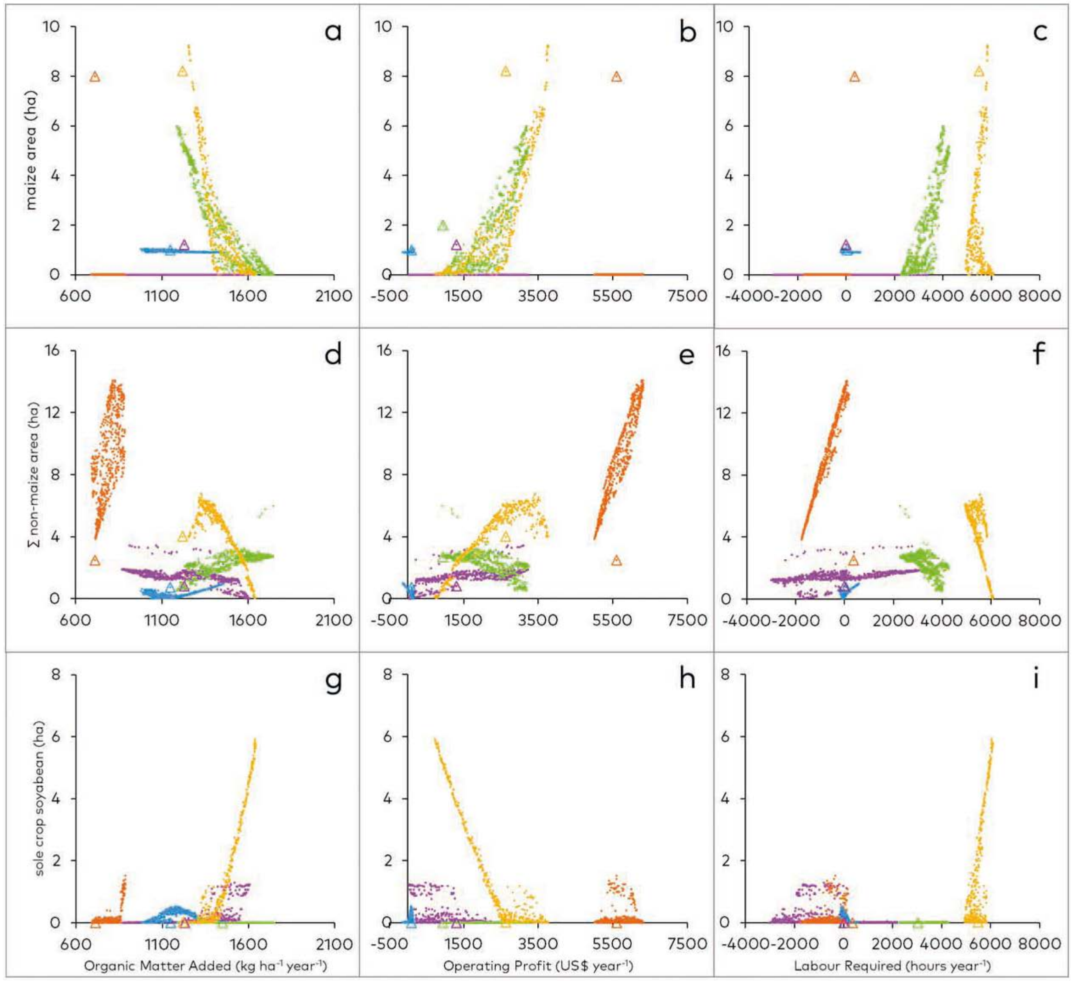


Figure 3.1 Performance of alternative farm configurations in terms of three farmer objectives, for five farm types in Eastern Zambia. The triangle symbols indicate the performance of the original farm configurations.



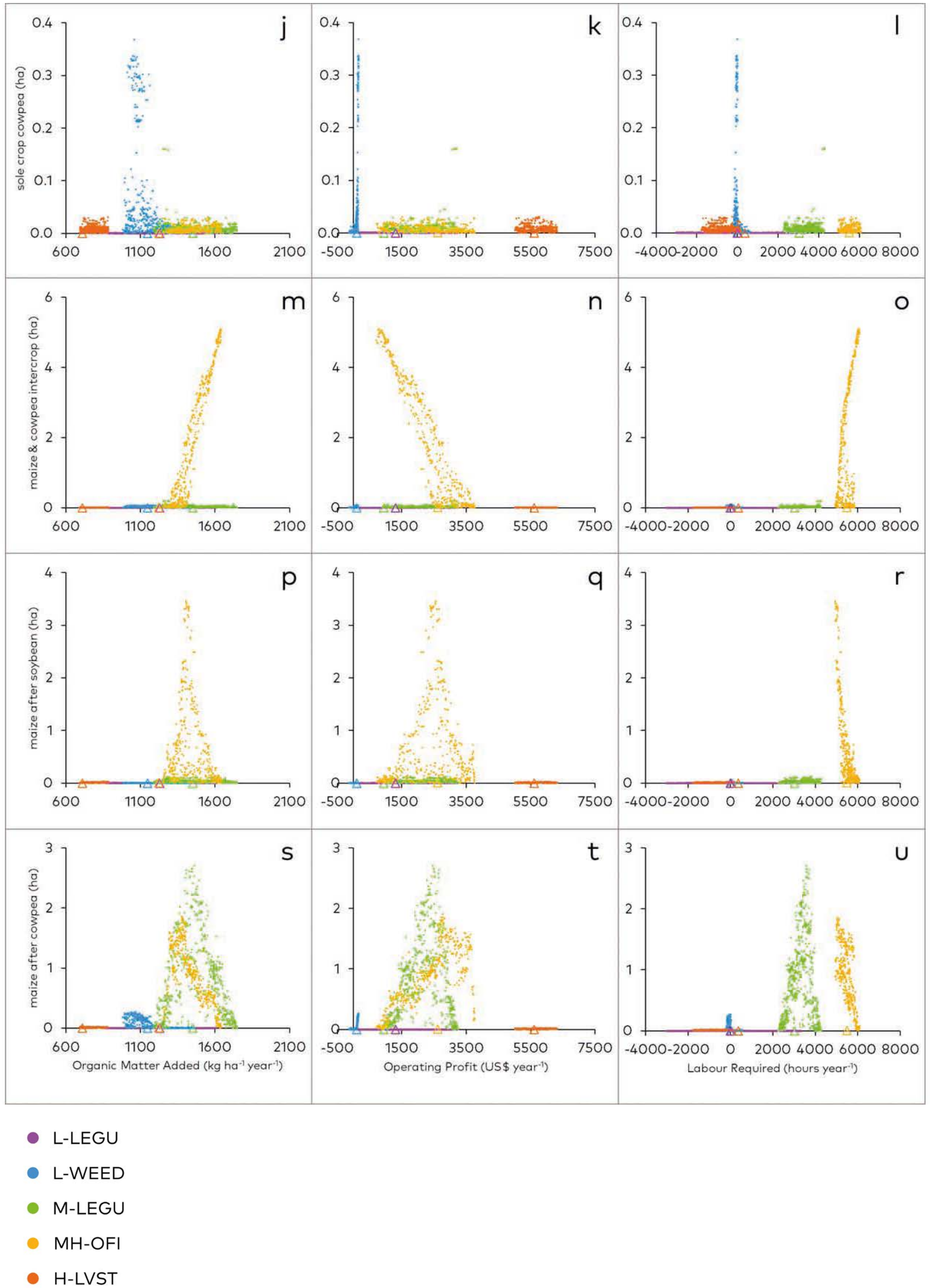


Figure 3.2 Performance of alternative farm configurations with different selected decision variables affecting changes in three farmer objectives, for five farm types in eastern Zambia. Colours of points refer to the different farm types. Each point refers to an alternative farm configuration for that farm type. Maize area, ∑ non-maize area, sole crop soybean, sole crop cowpea, maize & cowpea intercrop, maize after soybean and maize after cowpea are decision variables related to allocation of area to these crops by FarmDESIGN. The triangle symbols indicate the performance of the original farm configurations.

3.4 Discussion

Practices such as integrating legume as an intercrop or in rotation are viewed as a means for sustainable intensification. Indeed, intercropping maize with legumes such as cowpea or soybean may lead to increased land use efficiency, crop diversity, soil fertility and farm household income if competition between component crops is minimised while beneficial interactions are maximised (Giller *et al*., 2009; Baudron *et al*., 2012; Rusinamhodzi *et al*., 2012). We can see from the results that, at least for the MH-OFI type, an increase of intercropped maize and cowpea does not necessarily increase operating profit (Figure 3.2n). Including legumes in a rotation appears to have more potential to improve operating profit (Figure 3.2q, t) and it has slight synergies with labour (Figure 3.2r, u) for M-LEGU and MH-OFI. This means that these farmer could potentially reduce their labour loads whilst also earning greater income.

The surveyed farmers for the DC may have similar structural characteristics and farming orientation to the averages of the farm types; however, their personal motivations, desires and fears could diverge from others of the same farm type. For instance, the H-LVST farmer we surveyed had already been exposed to legume diversification intervention activities in his region, and explained he was keen to integrate legumes in his system, yet the model did not choose to include any large areas to intervention crops for his farm, the greatest area being to sole soybean (Figure 3.2g–i).

In FarmDESIGN, the windows of opportunities are defined using fixed assumptions on the achievable yields and market prices. However, in real conditions, farmers have to make decisions early in the cropping season under uncertainties on the future production and market situations. This decision-making process may be influenced by the farmer's personal background and socio-cultural factors. Moreover, it should be noted that a typology captures a 'snapshot in time' of a farming community (Kostrowicki, 1977). As farms are highly dynamic, farmers may change over time from one farm type to another. Interventions encouraging to improve farming systems by increasing the legume cultivation could be a driver for the change from one farm type to another (e.g. from L-WEED to L-LEGU and then M-LEGU) or even for the creation of a new type (e.g. H-LVST with legume).

3.5 Conclusion

The model exploration showed which intervention crops would be most suitable to which farm types taking into account their structural constraints and their objectives to maximise operating profit and organic matter added and to minimise their labour requirements. Sole legume crops like soybeans were found beneficial (i.e. higher profit, organic matter added to the soil and lower labour requirement) to L-LEGU, MH-OFI and H-LVST types, whereas L-WEED and M-LEGU types benefitted more from sole cowpea. For types L-WEED, M-LEGU and MH-OFI, including maize after the legume crop was found to be beneficial. Only the MH-OFI type was shown to have some benefit from an intercrop of maize and cowpea. The results show the need for differentiated solutions for different farm types in the Eastern province of Zambia and can act as a guideline for improved targeting of novel innovations for sustainable intensification that can possibly lead to improved adoption and hence enhanced livelihoods of smallholder farmers.

Future research can focus on a feedback of this data to the farmers aiming to gauge their opinions of the suitability of the interventions targeted at their farm type, and thereafter mapping their trajectories over time. Whether they adopt or reject the interventions, and the effect that this has on their farm type, would be of interest.

Chapter 4
Exploring solution spaces for nutrition-sensitive agriculture in Kenya and Vietnam

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◀ Complex cropping patterns in Mambai village, Vihiga, Western Kenya. Photo: Carl Timler

Abstract

Smallholder agriculture is an important source of livelihoods in South Asia and Sub-Saharan Africa. In these regions the highest concentrations of nutritionally vulnerable populations are found. Agricultural development needs to be nutrition-sensitive, and contribute simultaneously to improving household nutrition, farm productivity and environmental performance. We explored the windows of opportunities for farm development and the potential of crop diversification options for meeting household dietary requirements, whilst concurrently improving household economic performance in contrasting smallholder farm systems in Kenya and Vietnam. Farm and household features and farmer perspectives and priorities were integrated into a farm-household model that allowed quantification of a diverse set of nutritional, labour and productive indicators. Using a multi-objective optimization algorithm, we generated 'solution spaces' comprising crop compositions and management configurations that would satisfy household dietary needs and allowed income gains. Results indicated site-specific synergies between income and nutritional system yield for vitamin A. Diversification with novel vegetables could cover vitamin A requirements of 10 to 31 extra people per hectare and lead to greater income (25 to 185% increase) for some households, but reduced leisure time. Although the Vietnamese sites exhibited greater nutrient system yields than those in Kenya, the household diets in Kenya had greater nutrient adequacy due to the fact that the Vietnamese farmers sold greater proportions of their on-farm produced foods. We conclude that nutrition-sensitive, multi-method approaches have potential to identify solutions to simultaneously improve household income, nutrition and resource management in vulnerable smallholder farming systems.

4.1 Introduction

Sub-Saharan Africa and South-East Asia are two regions in the world where undernutrition is highly prevalent (Ahmed *et al.*, 2007, Gillespie *et al.*, 2015). In these regions the majority of the population depends heavily on agriculture for their food and income (Ahmed *et al.*, 2007, Gillespie *et al.*, 2015). Agricultural intensification has been promoted by many as the main pathway towards improved livelihoods of impoverished smallholder households (Tarawali *et al.*, 2011; Carsan *et al.*, 2014). In the last 50 years, this intensification has largely taken the form of increased use of external inputs such as improved seeds and/or livestock, agrochemicals and irrigation with recorded successes, such as yield increases, observed mostly in Asia, but with trade-offs that negatively impact environmental and human health (UNCTAD, 2014; FAO, 2017).

In South-East Asia the Green Revolution with its excessive reliance on external inputs contributed to decreased environmental health leading to reduced and more variable farm productivity and income as well as poorer nutrition (Ramankutty *et al.*, 2018). In contrast, the limited access to external inputs in Sub-Saharan Africa was also associated with adverse, undesirable consequences such as stagnating crop yields and decreased agricultural land expansion into native ecosystems (Carsan *et al.*, 2014; Mutoko *et al.*, 2014). Limited access to external inputs also constrains the maintenance, or increase in the productivity, of newly acquired lands. Use of marginal lands in combination with low external inputs, further exacerbates low farm productivity and contributes consequently to food insecurity and undernourishment among smallholder households. Additionally, to meet human energy requirements, agricultural policies have focused on improving the productivity of staple grains, particularly maize, wheat and rice, whilst neglecting fruit, vegetable, pulse and nut crops essential to address malnutrition in all its forms (under- and over-nutrition and micronutrient deficiencies) (DeFries *et al.*, 2015). This is particularly relevant for global public health, as poor diet quality and in particular, the lack of consumption of fresh fruits, vegetables and legumes is one of the primary risk factors for the global burden of disease (GBD 2016; Risk Factors Collaborators, 2017).

As a consequence of this focus on high-yielding staple crops (DeFries *et al.*, 2015), less supply and higher prices for nutritious foods make them inaccessible to households that need them most (Pingali, 2015; Sibhatu *et al.*, 2015). In Kenya, Masayi and Netondo (2012) show that the production area allocated to traditional staple crops of millet and sorghum as well as indigenous African vegetables has declined and subsequently also their consumption. In Vietnam, increased urbanization and incomes have led to changes in diets whereby traditional foods such as green vegetables, sesame, peanuts and tofu have become less important with increased consumption of animal proteins and heavily refined carbohydrates (Khan and Hoan, 2008, Lachat *et al.*, 2009).

The global trend to promote high-yielding staple foods in development projects and the resultant cereal-centric diets have not only contributed to micronutrient deficiencies and poor health but have also negatively impacted agrobiodiversity, reducing the number of different species and varieties produced. The diversity of species consumed is an important contributor to diet quality (Lachat *et al.*, 2017; DeClerck *et al.*, 2006). Powell *et al.* (2013) show the emergence of a 'hidden hunger' when insufficient food group diversity is consumed leading to micronutrient deficiencies. These deficiencies in vitamins and minerals (micronutrients) can cause severe and lifelong health issues (GBD 2016 Risk Factors Collaborators, 2017) and also contribute to the burden of malnutrition. Nutritious, indigenous foods, especially those that fall into the dark green leafy vegetable food group, are rich in calcium and folate as well as vitamins A, C and E, contributing to balanced diets (Yang and Keding, 2009). There is therefore a need for nutrition-sensitive agricultural interventions that diversify and increase productivity for both enhanced food and nutrition security. Stephens *et al.* (2018) summarize four key dimensions when assessing food security; food availability, food access, food utilization and finally the stability of the first three dimensions over time. The dimensions of food availability, food access and food utilization are addressed in this study. Because our methodological approach aims to develop, visualize and discuss windows of opportunities and snapshots of possible future scenarios (Groot and Rossing, 2011), we do not explicitly address the stability dimension. We use a multi-method approach to integrate farm and household characteristics and farmer objectives to determine how crop diversification could contribute to meeting dietary and income requirements in Kenyan and Vietnamese farming systems.

We use a farm-household model that first provides a baseline assessment of a farming system expressed in a broad set of productive, nutritional, socio-economic and environmental performance indicators. Then, through optimization of multiple, selected indicators the model enables systematic exploration of farm design and innovation options to meet farm production and household livelihood objectives. Rather than identifying scenarios (Figures 4.1a-b) or applying single or weighted or constrained optimization (Figures. 4.1c-e), we explore whole spaces of possible options available to farmers (Figures. 4.1f) (cf., Groot *et al.*, 2009). Such 'solution spaces' show a larger and broader set of alternative farm configurations that differ in performance of selected outcome indicators, i.e. the window of opportunities, and thereby allow the user to evaluate trade-offs and synergies between different farm management decisions and outcomes.

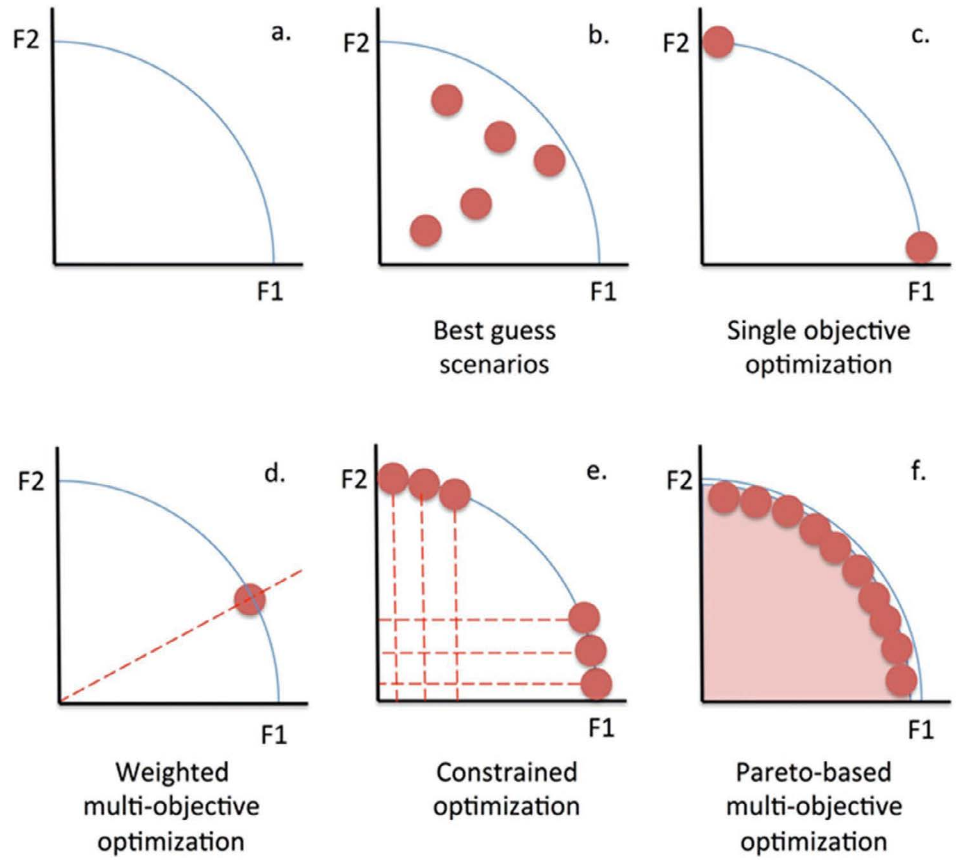

Figure 4.1 Solution spaces for different types of optimization of two objectives (F1 and F2) that are maximized.

The objective of our research was to (i) explore solution spaces defined by contrasting objectives, constraints and decision variables at the farm-household scale, (ii) examine the effects of nutrition-sensitive crop diversification interventions on the economic and human well-being indicators and (iii) compare crop diversification options and constraints between contrasting smallholder farming systems of Western Kenya and Northwest Vietnam.

4.2 Materials and Methods

We chose to study sites in the humid tropics in Kenya and Vietnam since both have highly prevalent undernutrition including deficiencies of vitamin A. In Kenya, approximately 84% of preschool children are vitamin A deficient, while in Vietnam approximately 12% suffer for vitamin A deficiency (WHO, 2009b). Both study sites also have distinct population and natural resource pressures, agricultural input use and market orientations. Within each country, two contrasting sites were selected differing in their structural and functional farm characteristics as well as their market orientation. The Kenyan sites have much higher population densities, lower use of agricultural inputs and, as they sell less of their own food produced, have less market orientation than the Vietnamese sites. Figures. 4.2 locates the case study sites and Table 4.1 compares their characteristics.

Farm and household specific data were collected using the survey tool IMPACTlite (Rufino *et al.*, 2013), in a semi-structured interview format in October and November 2014. For farm mapping and calculation of field areas, GPS readings were taken of field boundaries. To complement food consumption data collected using IMPACTlite, on two occasions per site, qualitative 24-hour food intake recalls were applied with women of reproductive age responsible for the household cooking of foods from ten pre-defined food groups (Kennedy *et al.*, 2010). The IMPACTlite survey tool differentiated foods obtained from on and off farm (e.g. market) production. Structured surveys were performed in both countries, with the same respondents as the 24-hr food intake recalls, to determine the frequency at which food items (Tables S4.1 and S4.2) were consumed by the household over the course of a year. We created one farm model per site to compare and contrast the differences in the modelled solution spaces across the four sites and between the two countries.

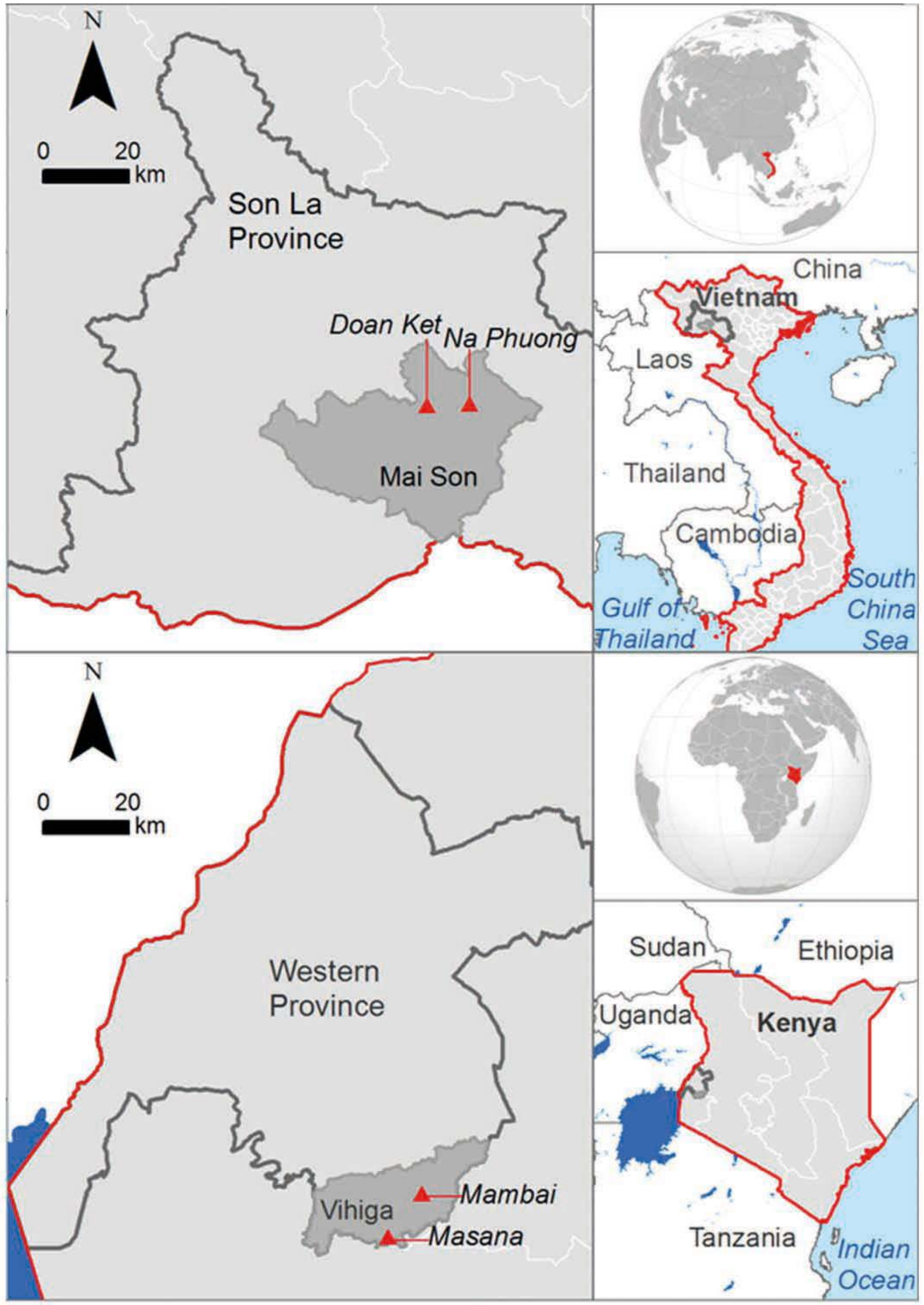

Figure 4.2 Location of Na Phuong and Doan Ket villages in Mai Son district, Son La Province in Northwest Vietnam and Mambai and Masana sub-locations in Vihiga County, Western Kenya.

Table 4.1 Characteristics of Western Kenya and Northwest Vietnam and the four selected case study sites.

Characteristic (Global databases)	**Western Kenya** Vihiga	
Altitude (m)	1 400 – 1 600	
Topography	Mostly rolling hills, some with rocky granite outcrops, and valleys with streams flowing mainly from northeast to southwest that all drain into Lake Victoria. Mambai has tea plantations and has steeper slopes than Masana which is on flatter, more gently sloping land. There are smaller scattered rocks in Masana and in Mambai there are occasional large boulders.	
Population density (capita km^{-2})	1 043	
Ethnicity	Luo & Luhya	
Climate	Equatorial	
Soils	Acrisols	
Staple food crop	Maize	
Ave. annual temperature (°C)	20.5	
Ave. annual rainfall (mm)	1 900, bimodal	
Agro-ecological zones	Upper Midland 1 (UM1) and Lower Midland 1 (LM1)	
Nutritional status	~84% of preschool children suffer from vitamin A deficiency (WHO, 2009b)	
Case study sites (own data)	**Mambai** n = 10	**Masana** n = 10
Farm size (ha) (ave.)	0.06 – 0.64 (0.33)	0.12 – 0.45 (0.29)
Ave. Household size	4.5	5.0
Main crops grown	Maize, beans, tea, napier, sweet potato, banana, kale, cassava	Maize, beans, napier, sweet potato, banana, kale, cassava
Main animal types	Cattle, goat, chicken	Cattle, goat, chicken
Market orientation	Sell tea as cash crop, small quantities of farm products sold locally	Small quantities of farm products sold, located closer to larger Kisumu markets
Subsistence# (%)	85	66

Table 4.1 Continuation

Characteristic (Global databases)	**Northwest Vietnam** Mai Son	
Altitude (m)	500 – 800	
Topography	The valleys have rivers running from northwest to southeast. There are scattered patches of forest. In Na Phuong there are steeper slopes with rain-fed maize on upper slopes and paddies with rice in the lowlands. In Doan Ket, there is a flatter landscape with more fish ponds and occasional hills with rocky outcrops where coffee is grown as a cash crop.	
Population density (capita km^{-2})	80	
Ethnicity	Thai Ethnic minority	
Climate	Humid Subtropical	
Soils	Orthic Acrisols and Chromic Luvisols	
Staple food crop	Paddy rice	
Ave. annual temperature (°C)	21.8	
Ave. annual rainfall (mm)	1 400 to 1 700, unimodal	
Agro-ecological zones	Northwest Agro Ecological Zone	
Nutritional status	~12% of preschool children suffer from vitamin A deficiency (WHO, 2009b)	
Case study sites (own data)	**Na Phoung** n = 8	**Doan Ket** n = 9
Farm size (ha) (ave.)	0.52 – 2.30 (1.20)	0.70 – 5.98 (1.95)
Ave. Household size	5.1	4.5
Main crops grown	Maize, rice	Maize, spring onion, cabbage, French beans, coffee
Main animal types	Chicken, pig	Fish, chicken
Market orientation	Sell almost all maize produced to animal feed processors	Sell most vegetables and coffee to local markets and maize to animal feed processors
Subsistence# (%)	11	2

Proportion of total food crop production that is consumed by the household

4.2.1 Modelling framework

Using the multi-objective optimization model FarmDESIGN (Groot *et al.*, 2012), the potential of new land-use and diet composition configurations was explored *vis-à-vis* their capacity to complete the household dietary composition needs. Nutrition-related indicators on dietary adequacy, diversity and food patterns (Estrada Carmona *et al.*, 2019) and household members as entities in the model and associated household level labour and income indicators (Ditzler *et al.*, 2019) were added to this bio-economic farm-household model. The nutrition-related indicators can now be analysed in relation to the socio-economic indicators such as profitability, household budgets and labour requirements, and environmental indicators such as land-use diversity, nutrient losses and soil organic matter accumulation (Table 4.2).

FarmDESIGN was used within the framework of the DEED cycle (Describe, Explain, Explore and Design) (Giller *et al.*, 2008). As a starting point, the farm household system is described through parameters covering household composition (members, on- and off-farm activities), farm environment (e.g. climate and soils), economics (e.g. farm expenses and labour prices), crops and animals with their related products (e.g. yields, labour required and destinations), manures, fertilizers, buildings and machinery. In the second step, the system is explained through economic, social, environmental and nutritional indicators. In the third exploration step, some of the parameters used to describe the system can be set as decision variables (i.e. with upper and lower limits on, for instance, crop areas), and some of the indicators used to explain the system can be set as constraints (i.e. upper and lower limits on animal's energy and protein requirements) or as outcome objectives to maximise or minimise. The model runs a Pareto-based Differential Evolution algorithm (Storn and Price, 1997) to generate numerous possible configurations and display them within a solution space. This algorithm is explained in Section 4.2.4. Finally, in the fourth step, a suitable solution can be chosen as a (re)design option for the farm.

4.2.2 Model indicators

Farm household systems in FarmDESIGN are explained by a wide range of indicators of which a selection is presented in Table 4.2. Various indicators can be compared before and after optimization enabling an overview of the effects of the optimization. Indicators describe the productivity of the farm, the socio-economic aspects of the household, the nutritional contribution to household requirements as well as the environmental performance of the farm.

Table 4.2 A selection of productivity, socio-economic, nutritional and environmental indicators present in the FarmDESIGN model.

Indicators	Units	Used as*	Type
Farm area	ha	constraint	Productivity
Livestock units	Tropical Livestock Units	indicator	Productivity
Nutrient system yield (NSY_r)	capita ha^{-1} yr^{-1}	objective	Productivity, Nutritional
Nutrient adequacy (A_r)	% of requirement	objective	Nutritional
Food group sufficiency	% of requirement	constraint	Nutritional
Dietary diversity score	-	indicator	Nutritional
Nutritional functional diversity	-	indicator	Nutritional
Nutrient self-sufficiency	% of consumption	indicator	Nutritional
Leisure time (T_L)	hours yr^{-1}	objective	Productivity, Socio-economic
Farm family labour (T_{tot})	hours yr^{-1}	indicator	Productivity, Socio-economic
Hired labour (L_H)	hours yr^{-1}	indicator	Productivity, Socio-economic
Off farm labour (L_{OF})	hours yr^{-1}	indicator	Productivity, Socio-economic
Off-farm income (I_O)	US$ yr^{-1}	indicator	Socio-economic
Household free budget (B_H)	US$ yr^{-1}	objective	Socio-economic
Operating profit (I_F)	US$ yr^{-1}	indicator	Socio-economic
Costs for food (C_F)	US$ yr^{-1}	indicator	Socio-economic
Other expenditure (C_E)	US$ yr^{-1}	indicator	Socio-economic
Nitrogen soil losses	kg ha^{-1} yr^{-1}	indicator	Environmental
Soil organic matter added	kg ha^{-1} yr^{-1}	indicator	Environmental

* 'Used as' presents the use of the indicator in the multi-objective optimization performed in this study either as a constraint or as an objective. Indicators not used in this study are designated 'indicator'. FarmDESIGN allows model users to select indicators and assign them as either a constraint or an objective, or both.

For (detailed) explanations of how productivity, socio-economic and environmental indicators are calculated in FarmDESIGN, we refer to Groot *et al.* (2012). Nutritional indicators as well as the changes to the household labour and economics calculations are described in more detail by Groot *et al.* (2017), Ditzler *et al.* (2019) and Estrada Carmona *et al.* (2019).

Here we choose four indicators as objectives: household free budget (B_H), leisure time (T_L), nutritional system yield for vitamin A (NSY_{vita}) and intake adequacy for vitamin A (A_{vita}) (Table 4.2). The maximization of the four objectives in the multiple-optimization facilitates assessing the synergies and trade-offs between improving household income while reducing labour load and vitamin A deficiencies that are present in the study areas (Ngare *et al.*, 2000; WHO, 2009b; NIN, 2010; Laillou *et al.*, 2012).

The objective household free budget, B_H (US\$ year^{-1}) is calculated as farm net income, I_F (US\$ year^{-1}) plus off-farm income, I_O (US\$ year^{-1}) less the sum of the cost of food, C_F (US\$ year^{-1}) and all other household expenses, C_E (US\$ year^{-1}). The objective leisure time, T_L (hours year^{-1}) is calculated as the annual sum of available time for on- or off-farm activities for all members of the household, T_{tot} (hours year^{-1}) less the hours spent on off-farm labour, L_{OF} (hours year^{-1}) and the labour hours required for farm management activities, L_{FA} (hours year^{-1}). L_{FA} (hours year^{-1}) is calculated as the sum of all labour hours required for crop cultivation, L_C (hours year^{-1}), plus the sum of all labour hours required for livestock keeping, L_A (hours year^{-1}), plus the sum of all labour hours required for general farm activities, L_G (hours year^{-1}) i.e. hours required for farm labour that is not directly attributable to a crop or animal enterprise and less the sum of the hours supplied by hired labour, L_H (hours year^{-1}).

The objective nutritional system yield for nutrient *r*, NSY_r (capita ha^{-1} year^{-1}) is calculated as follows:

$$NSY_r = \left(\frac{\sum_{i=1}^{n} F_i P_{r,i} + \sum_{j=1}^{m} F_j P_{r,j}}{R_r}\right) \times \frac{1}{S} \quad (1)$$

where *r* is a nutrient (e.g. vitamin A), F_i is the fresh weight produced (kg year^{-1}) of crop product *i* and $P_{r,i}$ is the content of nutrient *r* in crop product *i* (g kg^{-1}), F_j is the fresh weight (kg year^{-1}) of animal product *j* and $P_{r,j}$ is the content of nutrient *r* in animal product *j* (g kg^{-1}), R_r is the dietary requirement intake (DRI) for nutrient *r* for a person per year (g capita^{-1} year^{-1}) and S is the farm surface area (ha). The number of crop and animal products is indicated by *n* and *m*. This metric shows the number of people that can be supported per hectare by the current farm configuration in terms of nutrient *r* (adapted from DeFries *et al.*, 2015).

Food composition tables (FCT) were compiled specifically for this study (Tables S4.1 and S4.2). For Kenya, this was based on the national FCT of Tanzania (Lukmanji *et al.*, 2008) supplemented with data from other FCTs (Holtz *et al.*, 2012, SMILING D.5-a, 2013, Stadlmayr *et al.*, 2012, USDA and ARS, 2014 and West *et al.*, 1988). For Vietnam this was based on the Vietnamese FCT, SMILING D.5-a (2013), supplemented with data from other FCTs (Lukmanji *et al.*, 2008 and USDA and ARS, 2014). The total energy and nutrient demand per household were calculated as the sum of the energy and nutrient needs per household member with the use of the household composition data (age and gender) together with the individual Recommended Nutrient Intakes (RNI, level of intake that meets the needs for 97.5% of the population). To mimic the estimated average requirement (EAR, reflecting the level of intake that meets the needs of 50% of the population) we used the dietary reference intake of 70% RNI (Otten *et al.*, 2006) (cf. Table S4.5) comparable to other studies evaluating the nutrient adequacy of modelled diets. (Kujinga *et al.*, 2017; de Jager *et al.*, 2019; Samuel *et al.*, 2019). For the nutrients iron and zinc, the EAR (WHO, 2005) values were used, and adjusted to account for low bioavailability of these nutrients in the diets of these communities. These adjustments were also made following the methodology of Kujinga *et al.* (2017), de Jager *et al.* (2019) and Samuel *et al.* (2019). The total energy and nutrient intake per household were calculated based on the total food intake and the compiled FCTs.

The intake adequacy for a nutrient *r*, A_r (%) is calculated as follows:

$$A_r = \left(\frac{H_{I,r} - H_{D,r}}{H_{D,r}}\right) \times 100 \quad (2)$$

where $H_{I,r}$ is the household intake of a nutrient *r* (kg year^{-1}) and $H_{D,r}$ is the household required demand for nutrient *r* (kg year^{-1}).

In the optimization, to reflect the limited availability of arable land, the minimum household vitamin A requirement and a balanced feed ration for livestock, constraints were placed on total farm area, vitamin A adequacy and ruminant intake of dry matter, energy and protein (Tables S4.3 and S4.4).

In order to generate farm configurations that differ in economic productivity, labour demands, nutritional system yield of, and household intake adequacy for vitamin A, the areas of the currently grown crops and of new intervention crops, and the destination of crop products were defined as decision variables (Tables S4.3 and S4.4).

4.2.3 Intervention crops

Focus group discussions (FGDs) held in the study sites guided the selection of nutritious crops as part of the project's nutrition-sensitive interventions. Crops were selected for their market potential and their ability to close nutrient gaps, particularly vitamin A, through consumption. Selected crops, hereafter called 'intervention crops', included grains, pulses, dark green leafy vegetables and orange fleshed fruits and vegetables as these have a high vitamin A content. In Kenya, farmer-chosen crops included African nightshade (*Solanum americanum* L.), cowpea (*Vigna unguiculata* (L.) Walp.), crotalaria (*Crotalaria brevidens* Benth.), beans (*Phaseolus vulgaris* L.), groundnuts (*Arachis hypogaea* L.), kale (*Brassica oleracea* var. *acephala* L.), pumpkin (*Cucurbita maxima* Duch.), purple amaranth (*Amaranthus blitum* L.), soybeans (*Glycine max* (L.) Merr.) and spider-plant (*Cleome gynandra* L.). In Mambai, there were fewer intervention crops chosen in the FGDs than in Masana. Some intervention crops were also modelled as intercrops with maize (*Zea mays* L.). The modelled intervention crops can be seen in Table S4.3.

In Vietnam, 15 intervention crops were chosen by the farmers during the FGDs. Nonetheless, due to limited production data availability, we only used four in this modelling exercise: mustard greens (*Brassica juncea* (L.) Czern.), orange-fleshed (OF) sweet potato (*Ipomoea batatas*, Lam.), water spinach (*Ipomoea aquatica* Forsk.) and French beans (*Phaseolus vulgaris* L.). The same four intervention crops were used for both sites (Table S4.4).

Expected crop yields, labour requirements and cultivation costs were determined through combinations of survey data, expert opinion and literature review (Table 4.3). We set the area allocated to each intervention crop as a decision variable, ranging from zero area in the current situation up to the maximum farm area. The only exception being water spinach area for the farm Na Phuong where this intervention crop was restricted to the area currently used for irrigated rice (Table S4.3 and S4.4).

4.2.4 Multi-objective optimization

The multi-objective optimization uses a Pareto-based Differential Evolution algorithm (Storn and Price, 1997; Radhika and Chaparala, 2018). The complete mathematical explanation with the corresponding formulae, used in FarmDESIGN is described by Groot *et al.* (2012), however we briefly summarize the optimization process in this section. In the first iteration of the model the following steps occur. Two sets of new configurations are created, assigning random values within the ranges of the modelled decision variables to 80% of the configurations. The remaining 20% retain their original values. The solution space created by these two sets is extremely diverse. The variety in the decision variables (genotypes) creates diversity in farm performance that is measured by the indicators (phenotypes). New configurations from both populations are assigned a Pareto rank and a value indicating how crowded they are with respect to other solutions within the solution space. The configurations that outperform all other configurations in more than one of the set objectives have a rank of one. Removing these configurations, the ranking continues with the remaining configurations that outperform at least one objective, assigning them rank two, continuing until all configurations are ranked. Low ranking configurations are analogous to the fittest individuals in a population in evolutionary terms. The configurations from both populations are compared using a pairwise comparison and the fittest solutions are used as the 'parents' for the next iteration. If the compared solutions have the same Pareto rank then the least crowded configurations in the solution space have preference, ensuring that new spaces are explored rather than concentrating in one spot. In all following iterations only a new set of 'competitor' configurations are generated by uniform cross-over (i.e. allele by allele). The probability of cross-over and the amplitude of mutation are adjustable exploration parameters. The competitor configurations are compared with the parents by their Pareto rank and crowding and again the best phenotypes selected. Each iteration of the model can be seen as a new generation of farming household systems in a population that is progressing towards optimality. We used 4 000 iterations per run to reveal a Pareto frontier that forms with optimized solutions in a stable solution space.

4.3 Results

4.3.1 Case study farm descriptions

4.3.1.1 Mambai and Masana (Kenya)

Both farms made positive net incomes, yet at the household level, with the costs for the food consumed and other expenditures deducted, both had a negative household free budget (Table 4.4). In both farms, gross margins[1] for crop products were greater than gross margins[2] for animal products. Tea in Mambai and bananas in Masana provided the greatest absolute returns (US$ 165 and US$ 158, respectively) and traditional vegetables the greatest returns per hectare (US$ 7 956 ha^{-1} and US$ 3 418 ha^{-1} respectively).

1. Gross margin for crop products is calculated as returns (yield (kg ha^{-1}) * area (ha) * price (US$ kg^{-1})) less cultivation costs (US$ ha^{-1} * area).
2. Gross margin for animal products is calculated as returns (production (kg day^{-1}) * 365 days * price (US$ kg^{-1}) less annual costs (feeds + bedding + interest + general (US$)).

Table 4.3 Parameters for the annual expected yields, labour requirements, cultivation costs and fertilization costs for the modelled intervention crops in Kenya and Vietnam.

Crop	Crop Product(s)	Yield# (kg ha^{-1})	Labour (hours ha^{-1})	Cultivation costs (US$ ha^{-1})§	Fertilizer costs (US$ ha^{-1})
African nightshade	Leaves	2 500	5 000	2.95	118
Beans	Dried beans	1 200	6 000	2.46	236
Cowpea	Grains	500	6 000	2.95	236
	Leaves	1 300			
Crotalaria	Leaves	2 000	5 000	2.95	118
Groundnuts	Groundnuts unshelled	700	7 000	14.73	118
	Groundnut residues	700			
Maize & groundnuts	Maize	2 500	8 000	29.47	236
	Green maize residues	2 500			
	Dry maize residues	2 000			
	Groundnuts unshelled	500			
	Groundnut residues	500			
Soybean	Soybeans	1 200	7 000	19.64	236
	Residues	1 500			
Maize & soybean	Maize	2 500	8 000	29.47	236
	Green maize residues	2 500			
	Dry maize residues	2 000			
	Soybeans	1 000			
	Soybean residues	1 000			
Pumpkin	Leaves	4 000	8 000	2.95	118
	Fruits	3 000			
Purple amaranth	Grains	500	5 000	1.96	118
	Leaves	3 000			
Spider plant	Leaves	3 000	5 000	2.95	118
Kale	Leaves	5 000	7 000	1.96	236

Table 4.3 Continuation.

Crop	Crop Product(s)	Yield# (kg ha^{-1})	Labour (hours ha^{-1})	Cultivation costs (US$ ha^{-1})§	Fertilizer costs (US$ ha^{-1})
Mustard greens	Leaves	8 000	4 000	0.15	138
OF sweet potato	Tubers	10 000	2 000	0.53	0
Water spinach	Leaves	15 000	4 500	0.22	138
French beans	Fresh beans	15 000	7 000	0.26	171

Fresh harvested yield

§ Other than labour and fertilizer costs, 1 US$ = 101.81 Kenyan Shillings and 1 US$ = 22 665.46 Vietnamese Dong as at 30/11/2016

The areas dedicated to grow traditional vegetables were small, however the returns for these crops are high.

Nutritionally, both farms do not produce sufficient food on farm to supply household subsistence needs, in particular for dietary energy (kcal), calcium, iron, zinc, vitamin A and vitamin B12 (Figures 4.3a & 4.3c) and purchased foods are needed to supplement their diets (Figures 4.3b & 4.3d). Mambai and Masana households consumed 85% and 66% of their produced crop products, respectively. Households were able to sell some crop and animal produce (Table 4.4) to purchase food (mainly maize) to meet their energy need, however some micronutrients such as calcium, iron, zinc and vitamin A remained in deficit at the household level (Figure 4.3).

4.3.1.2 Doan Ket and Na Phuong (Vietnam)

Both farms had positive household free budgets largely supported by the sale of maize and French beans. Doan Ket had the highest net farm income (Table 4.4) with the greatest contribution stemming from animal production (annual gross margin US$ 3 892). The high annual returns were from the pig fattening enterprise they ran (US$ 6 689), which combined with their successful horticultural crop production (gross margin from cropping of US$ 2 231), resulted in Doan Ket having the highest household free budget.

Nutritionally, both modelled farms appeared to produce enough calories and micronutrients (with the exception of calcium and vitamin B12) to meet household demand (Figures 4.3e & 4.3g). However, the modelled Doan Ket household's diet appeared deficient in magnesium, calcium, iron, riboflavin, folate and vitamins A and C (Figure 4.3f); the farm sold much of its produce (98% of crop production), and their food purchases failed to meet the household nutrient demands. On the other hand, Na Phuong household consumed 11% of their crop produce, but still only achieved a similar level of household nutrient adequacy to Doan Ket, shown by the inadequate supply of magnesium, calcium, iron, riboflavin, folate and vitamins A and B12 (Figure 4.3h).

4.3.2 Exploration of solution spaces of case study farms

For the Mambai farm there was a synergy between household free budget and NSY_{vita} (Figure 4a), i.e. the household free budget increases with an increase in production of vitamin A. In contrast, the solution spaces of the other three farms indicated a trade-off between these two objectives. The synergy in the solution space of the Mambai farm was also visible in the similarity of the crop allocation trend noticeable as the household free budget and the NSY_{vita} increased in Figures. 5a and 5e, respectively. As household free budget and NSY_{vita} increased, area allocated to banana decreased and area allocated to the intercrop of maize, bean and kale increased.

For all farms there was a trade-off between household free budget and leisure time (Figure 4b). The more labour invested, with the corresponding reduction in leisure time, the more financial rewards there were to be gained. However, for the farms Doan Ket and to some degree Masana, there were portions within the solution space in which there was some synergy, allowing simultaneous increases in leisure time and free budget. For Doan Ket, this synergy was the result of configurations with an increasing area of crops with a high value crop product such as maize (sold for animal feed) combined with a decreasing area of fruit trees with their low labour requirement. In Masana, traditional vegetables that require more labour but have a higher vitamin A content were out-competed by the valuable cash crop lettuce. The trade-offs between household free budget and leisure time were also visible as mirrored patterns noticeable in the Figures. 4.5a and 4.5i, 4.5b and 4.5j, 4.5c and 4.5k and 4.5d and 4.5l.

The exploration yielded configurations where originally grown crops were replaced by the new intervention crops for only small percentages of the total farm area (Figure. 4.5). Most intervention crops were allocated to less than 5% of total farm area with a few exceptions. For Mambai and Masana, some additional area was allocated to kale (2-13%), and to pumpkin (0-6%). In Doan Ket, OF sweet potato (0-6%) and in Na Phuong, OF sweet potato (0-8%) and water spinach (0-2%) were introduced. The increased kale area in Mambai (both monocropped and intercropped with maize and bean) (Figures 4.5a & 4.5e) would allow for higher NSY_{vita} without increasing farm size (Figures 4.5a & 4.5c). The increases in the NSY_{vita} were achieved through allocation of even very small portions of land to the intervention crops kale, pumpkin, OF sweet potato and water spinach given their high vitamin A content.

Table 4.4 Modelled farm baseline characteristics: selected indicators from FarmDESIGN for four case study farms in Kenya (Mambai and Masana) and Vietnam (Doan Ket and Na Phuong).

Type	Indicator	Units	Kenya		Vietnam	
			Mambai	Masana	Doan Ket	Na Phuong
Household	Farm area	ha	0.22	0.42	1.17	0.64
	Household size	capita	6	7	5	5
	Livestock units	TLU	2.1	2.7	11.55	6.10
	Livestock density	TLU ha^{-1}	9.85	6.42	9.91	9.59
	Labour balance	hours yr^{-1}	0	0	0	0
Labour	Off farm labour	hours yr^{-1}	0	720	320	400
	Hired labour	hours yr^{-1}	217	0	0	0
	Farm family labour	hours yr^{-1}	5 678	3 483	5 697	6 230
Income	Farm net income	US$ yr^{-1}	1 312	1 053	4 864	3 110
	Off-farm income	US$ yr^{-1}	0	212	243	333
	Costs for food	US$ yr^{-1}	1 781	1 269	1 992	1 635
	Other expenditure	US$ yr^{-1}	584	184	833	439
	Total expenditure	US$ yr^{-1}	2 365	1 453	2 825	2 078
	Proportion food costs*	%	75	87	71	79
	Household free budget	US$ yr^{-1}	-1 053	-187	2 281	1 370
Environment	Soil organic matter added	kg ha^{-1} yr^{-1}	776	490	692	832
	Nitrogen soil losses	kg ha^{-1} yr^{-1}	98	71	193	327
Nutrition	NSY_{vita}	capita ha^{-1} yr^{-1}	8.3	2.7	6.1	4.2
	A_{vita}	%	-50	-42	-71	-32
	Degree of subsistence#	%	85	66	2	11

1 US$ = 101.81 Kenyan Shillings and 1 US$ = 22 665.46 Vietnamese Dong as at 30/11/2016.
TLU: Cow = 1.25, Heifer = 0.85, Calf = 0.55, Pig = 0.25, Goat = 0.2, Chicken = 0.01 and Fish = 0.005.
* Proportion of food costs in total expenditure (food costs + other expenditure).
\# Proportion of total crop production that is dedicated to household own consumption.

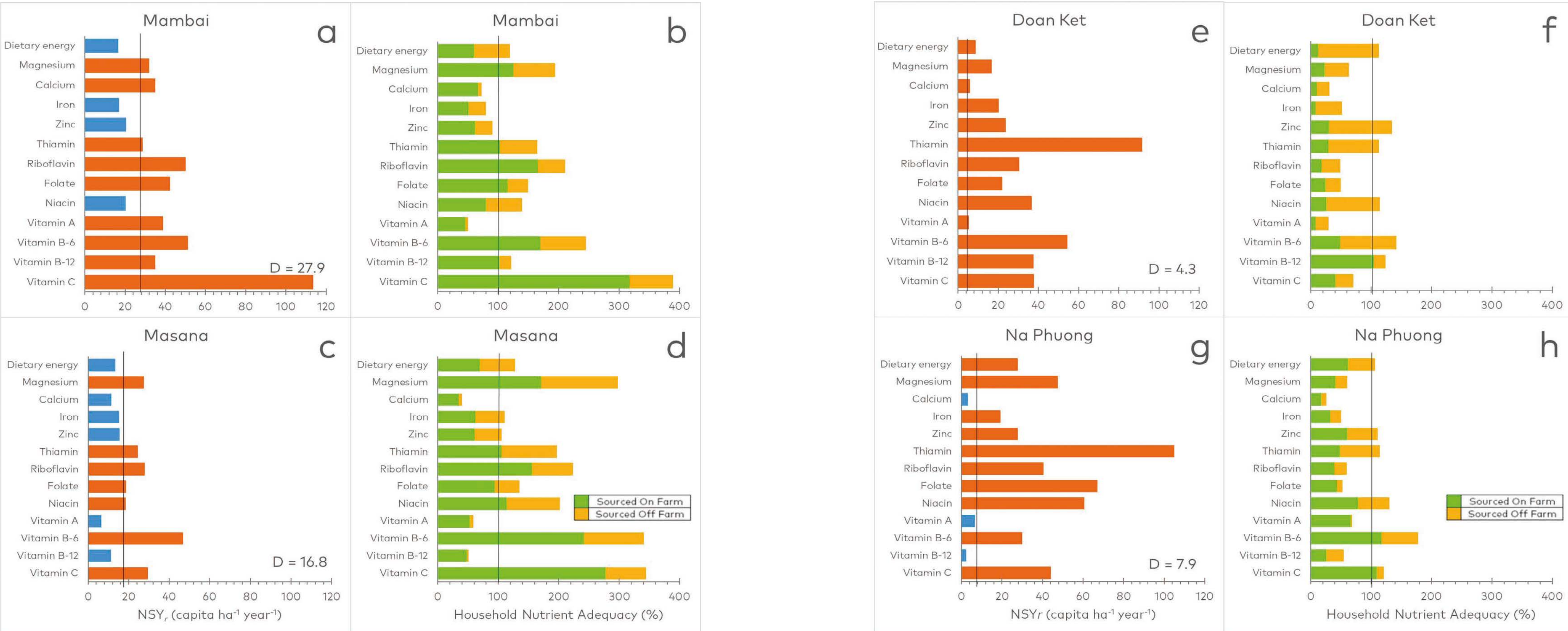

Figure 4.3 Nutrient System Yield (NSY*r*) and household nutrient adequacy for 13 nutrients for the four case study farms in Kenya (Mambai and Masana) and Vietnam (Doan Ket and Na Phuong). In graphs a, c, e and g the black vertical lines indicate the household member density (D) (household members divided by farm area and measured in capita ha-1), orange and blue indicate nutrients for which there is respectively, sufficient and insufficient produced on farm for home consumption. In graphs b, d, f, and h the black vertical lines indicate diets where 100% adequacy is reached, i.e. that the household's dietary requirement for that nutrient is fulfilled, the colours represent the source of the nutrients.

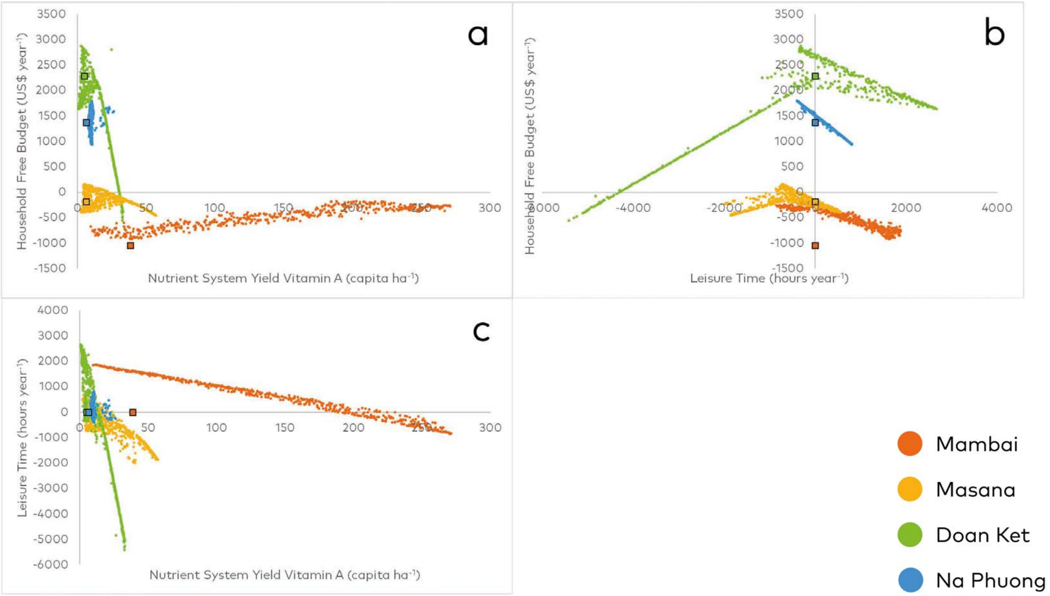

Figure 4.4 Performance of alternative farm configurations in terms of three objectives, household free budget, nutrient system yield for vitamin A and leisure time for the farms Mambai (orange), Masana (yellow), Doan Ket (green) and Na Phuong (blue). The coloured squares indicate the performance of the respective original farm configurations (baseline).

4.4 Discussion

We compared and contrasted the farming systems of the Kenyan and Vietnamese smallholder farmers showing how their diets and production patterns differed according to their resources and market orientation. We explored solution spaces and identified trade-offs and synergies at the farm scale between contrasting objectives and decision variables, and examined the effects of nutrition sensitive interventions on economic, social and nutritional indicators. The model generated crop compositions and space-time configurations that satisfied household nutritional requirements. Yet the intervention crops were not selected to replace currently grown crops to any large scale. However, we have demonstrated the use of an integrated model to explore these trade-offs and synergies at the farm-household scale.

The findings of this study show that, although the modelled Vietnamese farms produced ample nutrients to meet the nutritional requirements of the household, their actual consumed food (mostly purchased off-farm with most on-farm produce sold) reflected a diet deficient in several nutrients. Nationally, Vietnam has made drastic improvements in nutrition during the last two decades, however the last national nutrition survey indicated that vitamin C and iron deficiencies remain a problem (NIN, 2010). More recent regional studies find similar diet quality results and suggest that vitamin A, zinc, folate and vitamin B12 deficiencies are also present, with vitamin A, B12 and zinc deficiencies specifically identified as public health concerns (Laillou *et al.*, 2012). Furthermore, Nguyen *et al.* (2014) show that micronutrient intakes among poor populations in Northern Vietnam are sub-optimal. The Northwest region is predominately populated with minority ethnic groups, and the data used in this study were specifically from the Thai ethnic minority group. In the Northwest, minority ethnic groups suffer higher rates of economic and nutritional poverty compared to the national average. No studies have been published on diets within the Thai minority groups, however two studies looking at an aggregated population of minority groups in Vietnam show that micronutrient deficiencies and insufficient dietary intakes are still prevalent in these populations, particular in the remote rural areas of Vietnam (NIN, 2010; Huong *et al.*, 2013; Nguyen *et al.*, 2014).

The two Kenyan farms on the other hand, did not produce sufficient nutrients on farm as measured by the NSY*r* (Figures 4.3a and 4.3c), but supplemented their diet through the purchase of food off-farm, resulting in adequacy in the majority of the modelled nutrients Figures. 4.3b and 4.3d). A diagnostic survey carried out in a season of plenty (September to October 2014) and in a lean season (April 2015) in Vihiga, showed that more than 50% of children had intakes below the Estimated Average Requirements (EAR) for calcium, iron

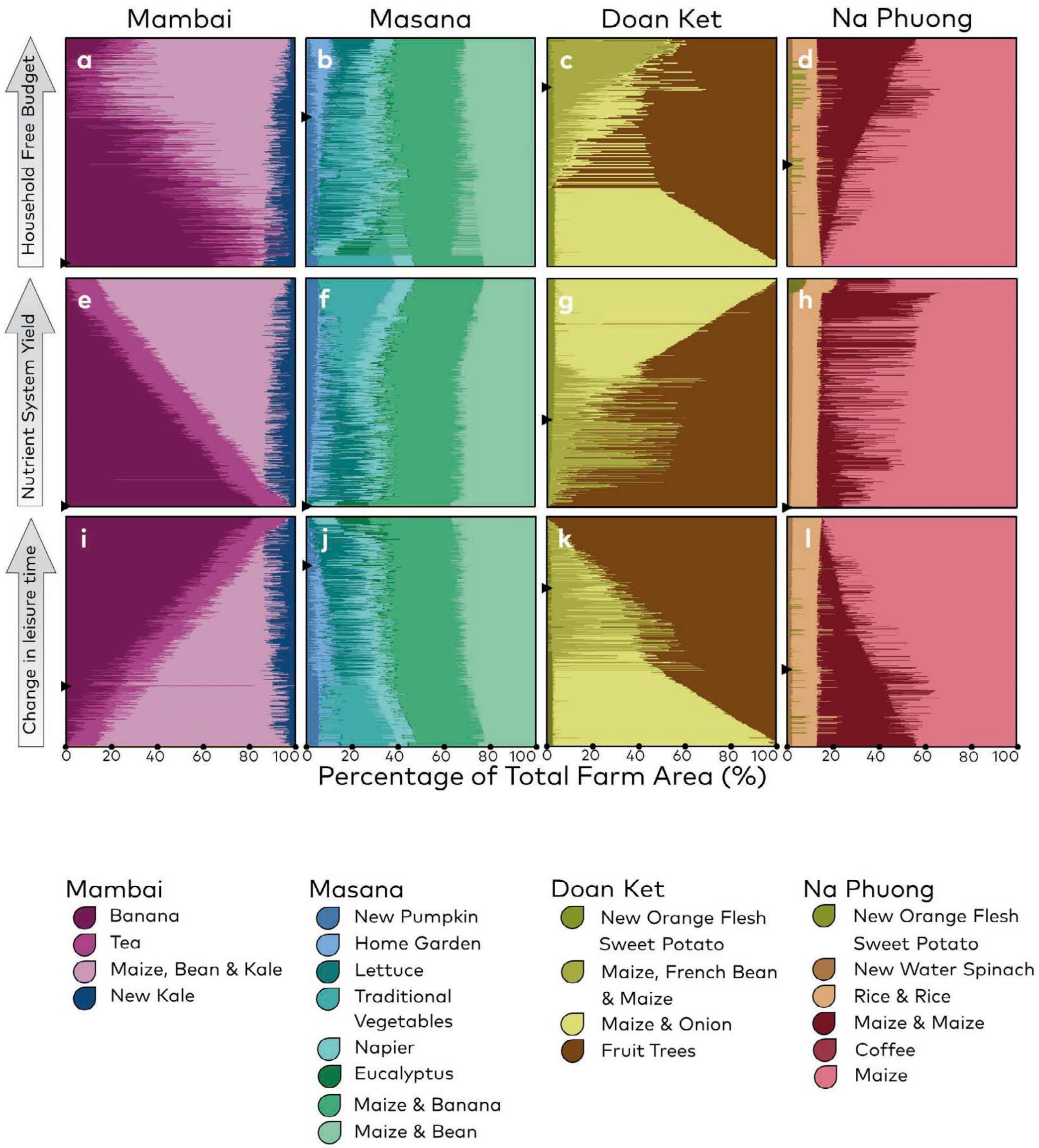

Figure 4.5 The allocation of different percentages of total farm area to the current and new land-use decision variables, for the complete set of alternative farm configurations generated for the farms Mambai, Masana, Doan Ket and Na Phuong horizontally arranged along an axis of increasing household free budget (top), increasing nutrient system yield (centre) and increasing change in household leisure time (bottom). The black triangle indicates the original value for the household free budget, the nutrient system yield and the leisure time for each farm.

and zinc in both seasons and for also for vitamin A and folate in the lean season (Oduor *et al.*, 2018). Another survey carried out in Vihiga in November to December 2015, showed that more than 50% of women had intakes below the EAR for iron, calcium and vitamin B12 (Bioversity unpublished data). That the Kenyan models did not produce sufficient nutrients on farm to satisfy the household requirements, should also be seen in the light of the fact that the population density in Vihiga is more than ten-fold of that in Mai Son (Table 4.1). The larger area of the Vietnamese farms, with similar numbers of household members to the Kenyan farms, means household densities (in capita ha^{-1}) are far higher in Kenya (see household density 'D' in Figure 4.3). So, even though the shortage of land in Vihiga is a major constraint to the smallholder farmers in that region, the results from this study show that the modelled Kenyan household's diets matched their requirements more adequately than the Vietnamese households.

Vietnamese household income was higher than Kenyan households, even though the relative proportions of food costs to other expenditure were similar (Table 4.4). Thus, the Vietnamese households had greater household free budgets. Furthermore, the agricultural policies in Northwest Vietnam support smallholder farmers with an adequate supply of agricultural inputs and markets for their produce (FFTC-AP, 2014; World Bank, 2016). In Kenya, these enabling policies and governmental support are, since the devolution of power to the counties in 2012, less effectively implemented in Western Kenya (Simiyu, 2015). Yet, despite being larger, more market oriented, and thus having a greater operating profit, the households in Vietnam were not adequately nourished (cf. Table 4.4 and Figure 4.3).

Regarding the solution spaces generated, crop choices by FarmDESIGN suggested crop space-time compositions that offered a synergy between NSY_{vita} and household income for the Kenyan farm models. Increasing areas grown to kale as a monocrop, or intercropped with maize, showed a trend of increasing income and supply of vitamin A for the modelled farm in Mambai. In Masana, closer to the urban centre of Kisumu, increasing the area of the cash crop lettuce, improved household income, but traditional vegetables improved NSY_{vita} to a greater extent in the model. This study however, did not examine the market potential of lettuce, a crop not widely grown in Vihiga County, yet the Masana farmer spoke favourably about this crop. The modelled farm in Doan Ket showed a trend of improved household income and NSY_{vita} replacing maize and onion bulbs with fruit trees. However, with the addition of more maize and French bean a trade-off between profit and labour emerged. In the Na Phuong farm, maize (with its easily saleable crop product that is not consumed by the household) was not out-competed by the intervention crops. Maize, a recent cash crop, appeared to provide great scope to increase household income, although the boom in its production has undesirable negative social and environmental consequences like increased erosion (Hauswirth *et al*., 2015; Castella *et al*., 2016) and is not consumed by households as it is sold for processing into animal feed.

The solution spaces shown in Figure 4.4 and 4.5 provide supporting material for farmer discussions. The suitability of different configurations in the solution spaces and the desirability of these novel configurations by the farmers has not been ascertained. That, theoretically the intervention crops have potential to improve household nutrition, does not imply that they will be adopted or utilised in the expected/modelled way for sale or consumption. However, the approach provides an opportunity to evaluate the impact of nutrition-sensitive agriculture interventions a priori which can guide farmers towards taking objective decisions.

The size and shape of the solution spaces depend on internal factors, as parameterized in FarmDESIGN, and external drivers like prices and policies, and these can reflect changes to private, public and social benefit as described by Groot and Rossing (2011). Further, solution spaces allow for the identification of efficient policy instruments (Parra-Lopez *et al*., 2009) and assessment of resilience and vulnerability of farm-household systems (Groot *et al*., 2016).

The novel approach taken in this study to add nutritional and household level indicators to the farm level bio-economic model FarmDESIGN provided a more integrated view of the effects of proposing changes to smallholder farming systems. We showed that FarmDESIGN is equally capable of analysing and exploring new options for farming systems along many gradients such as population densities, structural and institutional support, market integration and market orientation. The analysis and exploration took a wide range of multidisciplinary indicators into account: productivity, socio-economic, nutritional and environmental. Considering the wide range of indicators that can be included, FarmDESIGN is well positioned to analyse and optimise multiple Sustainable Development Goals (SDGs) as adopted by the United Nations (2015). This makes FarmDESIGN a comprehensive, multi-facetted tool for informing discussions between policy-makers, researchers, extension officers and farmers (or other stakeholders) on the effects of (sustainable) intensification and nutrition-sensitive agriculture interventions, or in highlighting the trade-offs and synergies between various SDGs in differing locations and circumstances.

This study had some limitations. The recording of household foods purchased off-farm was prone to error. The accuracy of the respondent's estimates of food quantities and consumption frequency over the past 12 months from memory could have been over- or underestimated. A "fixed" ratio was used to determine the weights bought from market and the weights home-consumed.

However, it remains difficult to record all the diversity of food sourced off-farm, with sources from many locations; wild harvested, gifts from relatives, food eaten at markets, in restaurants, etc. (Hebert *et al*., 1998; Deaton and Grosh, 2000; Kolodziejczyk *et al*., 2012). Water used for drinking was not recorded, and as water is potentially a good source of calcium (WHO, 2009a), when the recommended 1.5 litres per day are consumed, this might explain the low values for calcium seen in Figure 4.3. Assumptions were also made on an equal distribution of food within the household which is often not the case (Alderman *et al*., 1995; Haddad *et al*., 1996). Heads of households usually receive the largest portions with the choicest foods, while women and children, who are the most nutritionally vulnerable, often have difficulty accessing more nutrient-dense foods (e.g. meat, milk or eggs) (Udry *et al*., 1995; Hyder *et al*., 2005). Recording accurate labour data is also challenging (Arthi *et al*., 2018), and considering that leisure time was used as an optimization objective, possible imbalances between the estimated labour requirements for the novel intervention crops and the recorded labour for current crops could have resulted in intervention crops not being allocated to any large scale in the generated configurations presented in this study. The risks involved in making these changes were not included in this analysis.

The difference in household member density between the smallholder farms in Vietnam versus those in Kenya, (values for D, Figure 4.3) made an equal comparison difficult, however this was particularly useful in demonstrating the gradient of resource constraint, and how it increased with increasing population pressure while the proportion of on farm produced nutrients consumed increased. The Kenyan households had diets composed of greater proportions of on farm produced foods (more subsistence oriented) and had a more adequate diet that satisfied more nutrients requirement as opposed to the Vietnamese households that had a more market oriented dietary supply and a poorer dietary quality. The presence or absence of a link between agrobiodiversity and dietary diversity has been widely researched and documented (Termote *et al*., 2012; Keding and Cogill, 2013; Jones *et al*., 2014; Sibhatu *et al*., 2015; Ng'endo *et al*., 2016; Jones, 2017; Lachat *et al*., 2017; Rajendran *et al*., 2017; Mellisse *et al*., 2018; Sibhatu & Qaim, 2018). Although potentially a question that could be answered using the FarmDESIGN model, in this study we have not attempted to determine whether this direct link exists. What is certain from the current literature, is that the relationship is complex, can follow multiple pathways (Baudron *et al*., 2017) and can be confounded by many factors. Further research directions could focus on the participatory processes of dissemination and discussion of the results to, and with, the farmers.

4.5 Conclusions

We have presented a whole-farm multi-objective modelling exercise in four contrasting farm-household systems. The proposed multi-method approach and the model used, facilitates assessing and designing multifunctional agricultural landscapes for improved diet quality and incomes. This approach aims to jointly improve food and nutrition security, sustainable use of natural resources, biodiversity and ecosystem services conservation, both for human and environmental health. We have analysed and compared four case study villages in two countries, to examine the scope for and effect of different nutrition sensitive interventions on economic, environmental and nutritional indicators in contrasting contexts. We explored windows of opportunities for sustainable redesign and innovation in farming systems using the solution spaces generated by the whole-farm model FarmDESIGN to reveal trade-offs and synergies between contrasting objectives and decision variables. The relevant objectives analysed were household free budget, household leisure time and system-level yield of vitamin A. This integrated study allowed us to conclude that:

- Despite the modelled Vietnamese sites exhibiting greater nutrient system yields (NSY*r*) than those in Kenya, the modelled household diets in Kenya had greater nutrient adequacy due to the fact that the Vietnamese farmers sell greater proportions of their on-farm produced foods;
- According to our multi-objective model explorations, substitution of only small areas of the currently grown crops by 'intervention' crops would be sufficient to improve various nutritional and livelihood indicators, in both Kenya and Vietnam;
- Farmers in all locations faced the classic trade-off between income and labour, more income required more labour. Three of the four case study farms also showed a trade-off between household free budget and nutrient system yield for vitamin A (NSY_{vita}), while the case study farm in Mambai (Kenya) exhibited synergy between these two objectives.

Options exist for farmers to improve on the objectives analysed here. We were able to quantify possible improvements in these objectives, however further research and participation of farmers is required to ascertain the desirability and feasibility of these promising options, to be able to include risk assessments of new configurations, and to determine their perceptions on such diversification options.

Maize 'intercropped' with tea in Mambai, Vihiga, Western Kenya in 2015. Where tea bushes die, maize is planted in open spaces. Photo: Author's own. ▶

Lower slopes of the farm landscape in Mambai, Vihiga, Western Kenya in 2015. Eucalyptus trees form the boundary along a stream. Photo: Author's own. ▶

4.8 Supplementary Info

Table S4.1 Food Composition Table constructed for Kenya.

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
Units/100g fresh matter	kcal	mg	mg	mg	mg	mg	mg	µg	mg	µgRAE[3]	mg	µg	mg
maize	362	127	6	3.5	1.8	0.4	0.2	25	3.6	0	0.3	0	0
sorghum	339	171	25	4.1	1.6	0.3	0.1	14	2.8	7	0.2	0	0
millet	328	27	275	2.7	1.2	0.3	0.1	10	0.8	5	0.2	0	0
rice (polished)	358	36	8	0.6	1.1	0.1	0.1	6	1.1	0	0.1	0	0
oats	389	177	54	4.7	4	0.8	0.1	58	1	0	0.1	0	0
green mung beans	306	140	63	6.6	3.4	0.5	0.2	549	1.3	5	0.3	0	0
common beans	333	116	72	7.5	2.8	0.5	0.2	394	2.1	0	0	0.1	4.5
soybeans	415	280	278	15.8	5	0.4	0.7	133	1	3	0.2	0	3
groundnuts	567	168	92	4.6	3.3	0.3	0.1	126	14.3	0	0.3	0	0
cowpea grains	336	140	63	6.6	3.4	0.5	0.2	549	1.3	5	0.3	0	1.5
bambara nut	141	60	145	2.5	0.9	0.3	0.2	111	1.3	16	0.1	0	17
peas	317.8	112	57	4.4	4	0.77	0.18	274	3.1	11.66	0.174	0	2
pigeon peas	343	183	130	5.2	2.8	0.6	0.2	456	3	8.4	0.3	0	0
lentils	353	122	56	7.5	4.8	0.9	0.2	479	2.6	11.7	0.5	0	4.4
white sweet potato	117	25	41	0.8	0.4	0.107	0.083	15	0.761	0	0.285	0	3.3
orange sweet potato	123	20	43	0.9	0.4	0.112	0.088	16	0.8	630	0.3	0	3.4
taro/ arrow root	114.1	33	45	1.5	0.23	0.06	0.03	22	0.1	7.5	0.283	0	4
cassava	160	24	46	1.9	0.7	0.3	0.1	36	1.4	14	0.7	0	72
irish potatoes	58	25	5	0.4	0.3	0.1	0.2	75	4.2	0.6	0.7	0	18.6
plantain banana	122	37	3	0.6	0.1	0.1	0.1	22	0.7	338.1	0.3	0	18.4
yam	97	33	43	0.1	0.2	0.1	0.032	22	0.6	4	0.3	0	4.5
african nightshade	38	461	100.47	8.63	0	0.06	0.04	0.8	0.5	4.17	0	0	2
amaranth leaves	23	55	96.9	2.3	0.6	0.5	7.6	85	0.7	146	0.2	0	44.5
amaranth grains	371	248	159	7.6	2.9	0.1	0.2	82	0.9	0.6	0.6	0	4.2
jew's mallow	59	54	360	5.7	0.44	0.15	0.53	112	1.2	261	0.31	0	80
pumpkin leaves	19	28.4	114.5	0.6	1.1	0	8.5	118	0.4	550	0.2	0	24.5
pumpkin fruits	26	12	21	0.8	0.32	0.05	0.11	16	0.6	426	0.061	0	9
spider plant	27	25	76	1.8	0.51	0.04	0.16	50	0.7	113	0.3	0	36.5
cowpea leaves	37	62	49.7	0.8	1.4	0.1	8.3	104	0.9	519	0.5	0	32.4
coriander leaves	23	26	67	1.77	0.5	0.067	0.162	62	1.114	337	0.149	0	27

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
bean leaves	27	8	60	1.8	0.3	0.3	0.16	72	1.01	32	0.16	0	23.8
broccoli	34	21	47	0.7	0.4	0.1	0.1	63	0.6	186.9	0.2	0	89.2
cauliflower	29.6	22	26	1.4	0.2	0.11	0.1	57	0.6	1.33	0.222	0	70
cabbage	25	12	40	0.5	0.2	0.1	0.04	43	0.2	5	0.1	0	36.6
kale	49	47	150	1.47	0.56	0.11	0.13	141	1	500	0.271	0	120
lettuce	13	18	38	1.1	0.4	0.3	0.09	38	0.2	740.5	0.09	0	30
spinach	23	79	99	2.71	0.53	0.078	0.189	194	0.724	469	0.195	0	28.1
french beans	73.2	26	26	0.7	0.01	0.34	0.19	108	1.6	30	0.428	0	25
tomatoes	21	11	5	0.5	0.1	0.1	0.1	15	0.6	87	0.1	0	19
cucumber	16	15	23	1	0.18	0.03	0.04	7	0.1	23	0.04	0	5
eggplant	23	14	12	0.7	0.16	0.03	0.04	22	0.5	6.67	0.084	0	3
carrots	41	12	33	0.3	0.2	0.1	0.1	19	1	841	0.1	0	5.9
capsicum pepper	19	10	10	0.5	0.2	0.1	0.1	44	1.4	78	0.4	0	218
chili pepper	23	12	7	0.43	0.25	0.054	0.085	18	0.979	313.16	0.291	0	190
garlic	149	25	181	1.7	1.2	0.2	0.1	3	0.7	2.7	1.2	0	31.2
onions bulbs	40	10	23	0.2	0.2	0.074	0.043	19	0.1	0.6	0.1	0	7.4
spring onion	22.4	23	80	1	0.44	0.03	0.1	16	1	100	0.071	0	60
ginger	66	17	33	0.3	0.3	0.1	0	23	0.3	0	0.2	0	8
sugarcane	26	2	6	0.1	0	0	0	0	0	0	0	0	0
mushroom	22	9	3	0.5	0.5	0.081	0.402	16	3.607	0	0.104	0.04	2.1
apple	46.8	3	19	2.5	0.2	0.04	0.03	3	0.2	5.42	0.041	0	7
papaya fruit	39	10	24	0.1	0.1	0.02	0.02	38	0.3	135	0.03	0	62
mango fruit	65	9	10	0.1	0.09	0.1	0.1	14	0.6	38	0.1	0	27.7
sweet banana	89	27	5	0.3	0.2	0	0.1	20	0.7	3	0.4	0	8.7
lemon/lime	29	8	26	0.6	0.1	0.1	0	11	0.1	1	0.1	0	53
orange fruit	47	10	40	0.1	0.1	0.1	0.1	30	0.3	8	0.1	0	53
grapefruit	32	8	12	0.1	0.1	0	0	10	0.3	278.1	0	0	34.4
peach	68.3	15.7	10.5	0.4	0.3	0	0.1	7	1.4	171	0	0	11.6
water melon	30	10	7	0.2	0.1	0.033	0.021	3	0.2	28	0.045	0	8.1
jackfruit	94	37	34	0.6	0.4	0.1	0.1	14	0.4	15	0.1	0	6.7
passion fruit	43	7	5	0.1	0.1	0	0.1	3	1	54	0.1	0	7
pineapple	50	12	13	0.3	0.1	0.1	0	18	0.5	58	0	0	47.8
guava	68	22	18	0.3	0.2	0.1	0	49	1.1	31	0.1	0	228.3
avocado	160	29	12	0.6	0.6	0.1	0.1	81	1.7	7	0.3	0	10

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
loquat	47	13	16	0.3	0.1	0	0	14	0.2	458.4	0.1	0	1
cape gooseberry	53	10	9	1	0.1	0.1	0	47	2.8	216	0.02	0	11
grapes	67.6	7	17	0.6	0.07	0.06	0.04	2	0.2	6.58	0.086	0	3
plums	46	7	6	0.2	0.1	0	0	5	0.4	103.5	0	0	9.5
white sapote	134	30	39	1	0.2	0	0	36	1.8	123	0.06	0	20
vegetable oil	862	0	0	0	0	0	0	0	0	0	0	0	0
margarine	716	0	0	0	0	0.01	0.037	0	0	1073.1	0	0.1	0
infant porridge	300	100	733	10	2.4	0.4	0.6	0.035	5	159.74	0.5	0.3	2.3
weetabix	371	92	57	12.86	1.72	1.929	0.98	46	5.714	2.7	0.46	0	0
pasta	371	22	15	1.2	0.1	0.1	0.1	18	1.7	0	0.1	0	0
biscuit/cakes	434	27	119	1.2	0.8	0.1	0	31	1.1	0	0	0	0
bread loaf	274	27	10	0.5	0.9	0.1	0.1	31	0.9	0	0	0.1	0
mandazi	426	16	60	1.1	0.4	0.23	0.2	46	1.51	3	0.03	0.24	0.1
chapatti	275	16	86	1.4	0.8	0.267	0.097	24	2.142	0	0.034	0	0
salt	0	2	45	0.1	0	0	0	0	0	0	0	0	0
sugar	387	0	1	0.1	0	0	0	0	0	0	0	0	0
honey	327	2	5	0.9	0.22	0	0.04	2	0.2	0	0.024	0	4
fruit juice	42	10	11	0.1	0.1	0.1	0	30	0.3	8	0.1	0	53
soda drink	48	0	5	0.1	0.1	0	0	0	0	0	0	0	0
tea	1	2	2	0	0	0	0	5	0	0	0	0	0
coffee	1	3	2	0	0	0	0.1	2	0.2	0	0	0	0
beer	43	6	4	0	0	0.01	0.03	6	0.51	0	0.05	0.02	0
spirit alcohol	263	0	0	0	0	0	0	0	0	0	0	0	0
beef meat	267	15	3	1.1	2.7	0.1	0.1	4	2.2	0	0.2	1.3	0
goat meat	109	25	13	2.8	4	0.1	0.5	5	3.7	0	0.26	1.1	0
pork meat	632	6	14	0.26	0.6	0.16	0.09	5	2.63	26	0.143	0.67	0.7
chicken meat	200	14	9	1	1.3	0.1	0.2	4	4.1	42	0.2	0.2	0
duck meat	267.4	15	13	1.8	1.36	0.07	0.15	13	4.7	270	0.19	0.25	2.8
pigeon meat	340	22	45	5.4	2.2	0.1	0.28	6	5.3	73	0.41	0.4	5.2
quail meat	155	12.7	15	2.9	3	0.12	0.5	3.47	5.8	45	0.24	0.23	0
rabbit meat	114	29	12	3.2	1	0	0.1	7	6.5	0	0.53	5.6	0
fresh fish	98	21	7	0.3	0.3	0.1	0.1	51	0.7	0	0.5	1.6	17
dried fish	413	35	43	2.6	1.3	0.159	0.257	93	15.951	0	0.627	6.12	0
small dried fish	84	22	9	0.3	0.5	0.2	0.1	8	1.9	12	0.1	2.3	1

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
insects	340	0	12	1	8.4	0.67	0.23	3	4.1	0	0.3	1.56	0
eggs	155	10	50	1.2	1.1	0.1	0.5	44	0.1	169	0.1	1.1	0
fresh cow milk	60	11	115	0.1	0.4	0	0.2	5	0.1	28	0.042	0.4	0
fresh goat milk	69	14	134	0.05	0.3	0.048	0.138	1	0.277	57	0.046	0.07	1.3
milk powder	496	81	851	0.7	3	0.3	1.3	44	0.7	407	0.4	3	7
animal cooking fat	896.4	0	0	0	0.11	0.019	0	0	0	0	0	0	0
butter	717	2	17	0	0.1	0	0.2	3	0.7	684	0	0.2	0
cheese	380.1	28	760	0.5	3.11	0.1	0.51	18	0.1	294.67	0.074	0.83	0.5
yoghurt	60.9	12	120	0.1	0.59	0.04	0.2	7	0.1	26.83	0.032	0.37	0.7

3. Where figures were only available for Vitamin A in IU, a factor of 0.3 was used to get Vitamin A Retinol Activity Equivalents (FAO:WHO, 2001).

Table S4.2 Food Composition Table constructed for Vietnam.

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
Units/100g fresh matter	kcal	mg	Mg	mg	mg	mg	mg	µg	mg	µgRAE[4]	mg	µg	mg
bamboo shoot	11.0	88	18	0.9	1.1	0.11	0.09	5.6	0.6	1.25	0.19	0	9
banana	66.3	27	12	0.5	0.32	0.04	0.07	20	0.6	3.21	0.37	0	6
beef	166.5	15	10	2.7	4.05	0.1	0.17	13	4.2	0	0.65	0.98	1
bitter melon	15.6	17	18	0.6	0.8	0.07	0.04	72	0.3	23.54	0.043	0	22
black beans	325.3	165	56	6.1	3.65	0.5	0.21	444	1.8	2.5	0.29	0	3
cabbages	29.4	13	48	1.1	0.81	0.06	0.05	43	0.4	5.42	0.1	0	30
carrots	39.2	12	43	0.8	1.11	0.06	0.06	19	0.4	887.71	0.14	0	8
chicken	199.1	29	12	1.5	1.5	0.15	0.16	6	8.1	120	0.35	0.31	4
chicken egg	165.6	11	55	2.7	0.9	0.16	0.31	47	0.2	700	0.14	1.29	0
chili	23.0	12	7	0.43	0.25	0.05	0.09	18	0.98	156.58	0.29	0	190
coriander	23.0	26	67	1.77	0.5	0.067	0.162	62	1.11	337	0.149	0	27
duck	199.1	29	12	1.5	1.5	0.15	0.16	6	8.1	120	0.35	0.31	4
eggplant	20.0	18	12	0.7	0.3	0.03	0.04	22	0.5	2	0.084	0	3
flat pea	42.0	24	43	2.08	0.27	0.15	0.08	42	0.6	54	0.16	0	60
french beans	73.2	26	26	0.7	0.01	0.34	0.19	108	1.6	15	0.43	0	25
fresh fish	99.5	29	49.7	0.53	1.48	0.12	0.06	25.4	1.64	0	0.19	1.53	0
fresh milk	74.4	16	120	0.1	0.4	0.05	0.19	5	0.1	51.83	0.04	0.44	1
garlic	118.0	8	24	1.5	0.9	0.24	0.03	0	0.9	0	1.24	0	10
green maize	246.0	73	5	1.4	1.1	0.5	0.2	105	3.6	9	0.1	0	14
green mung beans	306.0	140	63	6.6	3.4	0.5	0.2	549	1.3	6	0.3	0	4.8
insects	124.0	18	73	2	0.9	0.43	0.74	71.89	0	80.88	0.14	8.99	14.4
longan	60.0	21	0.13	10	0.05	0.14	0.3	0	0.3	0	0	0	0.03
maize yellow grain	246.0	73	5	1.4	1.1	0.5	0.2	105	3.6	9	0.1	0	14
mango	68.7	2	10	0.4	0.56	0.05	0.05	14	0.3	38.25	0.13	0	30
mung bean	327.6	270	64	4.8	1.1	0.72	0.15	625	2.4	2.5	0.382	0	4
mustard greens	16.2	23	89	1.9	0.9	0.07	0.1	187	0.8	525	0.18	0	51
onion bulb	16.0	18	56	1.3	0.2	0.03	0.09	64	0.9	83.33	0.23	0	19
onion welsh	22.4	23	80	1	0.44	0.03	0.1	16	1	49.83	0.071	0	60
orange	37.2	10	34	0.4	0.22	0.08	0.03	30	0.2	11.21	0.06	0	40
orange flesh sweet potato	103.0	20	28	0.5	0.3	0.1	0.1	23	0.6	709	0.2	0	25
oranges	37.2	10	34	0.4	0.22	0.08	0.03	30	0.2	11.21	0.06	0	40

Nutrient	Energy	Mg	Ca	Fe	Zn	Thiam.	Ribofl.	Folate	Niacin	Vit A	Vit B6	Vit B12	Vit C
paddy rice	344.2	14	30	1.3	1.5	0.1	0.03	9	1.6	0	0.15	0	0
pak choy	13.0	19	105	0.8	0.19	0.04	0.07	66	0.5	223	0.19	0	45
papaya	35.0	8	40	1.4	0.1	0.02	0.02	38	0.4	55	0.019	0	54
peanuts	572.5	185	68	2.2	1.9	0.44	0.12	240	16	0.83	0.35	0	0.8
pork	139.0	32	6.7	0.96	2.5	0.9	0.18	5	4.4	2	0.42	0.84	0.8
pumpkin	26.5	10	24	0.5	0.1	0.06	0.03	16	0.4	369.17	0.06	0	8
taro	114.1	33	45	1.5	0.23	0.06	0.03	22	0.1	3.75	0.28	0	4
tomato	20.0	15	12	1.4	0.74	0.06	0.04	15	0.5	37.42	0.08	0	40
water melon	15.8	15	8	0.2	0.11	0.04	0.04	3	0.2	28.5	0.05	0	7
water spinach	22.8	15	100	1.4	0.35	0.1	0.09	194	0.7	466.42	0.2	0	23

3. Where figures were only available for Vitamin A in IU, a factor of 0.3 was used to get Vitamin A Retinol Activity Equivalents (FAO:WHO, 2001).

Table S4.3 Objectives, decision variables modified, constraints applied and exploration parameters used during the generation of alternative farm configurations for the farms Mambai and Masana, Kenya.

Farm		Original	Min	Max
Mambai	**Objectives**			
	Household Free Budget (US$ year-1)	-1 053		✓
	Nutrient System Yield Vitamin A (capita ha-1)	38.7		✓
	Household Leisure time (hours year-1)	0		✓
	Vitamin A Deviation (%)	-50.1		✓
	Decision Variables			
	Maize Bean Kale Area (ha)	0.0200	0	0.2152
	Maize Bean Area (ha)	0.0228	0	0.2152
	Tea Area (ha)	0.0712	0	0.2152
	Banana Area (ha)	0.0244	0	0.2152
	Napier Area (ha)	0.0225	0	0.2152
	Eucalyptus Area (ha)	0.0393	0	0.2152
	Home garden Area (ha)	0.0150	0	0.2152
	New African Nightshade Area (ha)	0	0	0.2152
	New Cowpea Area (ha)	0	0	0.2152
	New Maize Groundnuts Area (ha)	0	0	0.2152
	New Sukuma Wiki Area (ha)	0	0	0.2152
	New African Nightshade leaves to Home Use (-)	1	0	1
	New Cowpea Grains to Home Use (-)	1	0	1
	New Cowpea Leaves to Home Use (-)	1	0	1
	New Maize Grain to Home Use (-)	1	0	1
	New Green Maize Stalks to Soil (-)	0	0	10
	New Dry Maize Stalks to Soil (-)	1	0	10
	New Groundnuts in shell to Home Use (-)	1	0	1
	New Sukuma Wiki Leaves to Home Use (-)	1	0	1
	Dry Maize Stalks to Animals (-)	1	0	10
	Bean Residue to Animals (-)	0	0	10
	Dry Maize Stalks to Animals (-)	1	0	10
	Bean Residue to Animals (-)	0	0	10
	Grazing Grass to Animals (kg DM year-1)	2 243	0	3 000
	Napier Purchased to Animals (kg DM year-1)	450	0	2 000
	Constraints			
	Ruminant Dry Matter Intake (%)	0	-999	0
	Ruminant Energy Requirements (%)	2.85	-5	5
	Ruminant Protein Requirements (%)	5.43	-5	30
	Total Farm Area (ha)	0.2152	0.1940	0.2370
	Vitamin A Deviation (%)	-50.1	-51	50
	Exploration Parameters			
	Amplitude (F)	0.15		
	Probability (CR)	0.85		
	Number of solutions	500		
	Number of iterations	4 000		
Masana	**Objectives**			
	Household Free Budget (US$ year-1)	-187		✓
	Nutrient System Yield Vitamin A (capita ha-1)	6.4		✓
	Household Leisure time (hours year-1)	0		✓
	Vitamin A Deviation (%)	-42.3		✓
	Decision Variables			
	Maize Bean Area (ha)	0.1432	0	0.4161
	Maize Banana Area (ha)	0.1364	0	0.4161
	Eucalyptus Area (ha)	0.0533	0	0.4161
	Napier Area (ha)	0.0383	0	0.4161
	Traditional Vegetables Area (ha)	0.0118	0	0.4161
	Lettuce Area (ha)	0.0181	0	0.4161
	Home garden Area (ha)	0.0150	0	0.4161
	New African Nightshade Area (ha)	0	0	0.4161
	New Beans Area (ha)	0	0	0.4161
	New Cowpea Area (ha)	0	0	0.4161
	New Crotalaria Area (ha)	0	0	0.4161
	New Groundnuts Area (ha)	0	0	0.4161
	New Maize Groundnuts Area (ha)	0	0	0.4161
	New Soybeans Area (ha)	0	0	0.4161
	New Maize Soybeans Area (ha)	0	0	0.4161

Farm		Original	Min	Max
	New Pumpkin Area (ha)	0	0	0.4161
	New Purple Amaranth Area (ha)	0	0	0.4161
	New Spider Plant Area (ha)	0	0	0.4161
Masana	New Sukuma Wiki Area (ha)	0	0	0.4161
	Bean Residues to Soil (-)	0	0	10
	Crotalaria Residues to Soil (-)	1	0	10
	Groundnut Residues to Soil (-)	0	0	10
	Green Maize Stalks to Soil (-)	0	0	10
	Dry Maize Stalks to Soil (-)	1	0	10
	Groundnut Residues to Soil (-)	0	0	10
	Soybean Residues to Soil (-)	0	0	10
	Green Maize Stalks to Soil (-)	0	0	10
	Dry Maize Stalks to Soil (-)	1	0	10
	Soybean Residues to Soil (-)	0	0	10
	Dry Maize Stalks to Soil (-)	1	0	10
	Bean Residues to Soil (-)	0	0	10
	Dry Maize Stalks to Soil (-)	1	0	10
	Banana Leaves to Soil (-)	0	0	10
	Assorted Stems to Soil (-)	0	0	10
	Grazing Grass to Animals (kg DM year^{-1})	2 308	0	5 000
	Constraints			
	Ruminant Dry Matter Intake (%)	0	-999	0
	Ruminant Energy Requirements (%)	-3.78	-5	5
	Ruminant Protein Requirements (%)	-4.7	-5	30
	Total Farm Area (ha)	0.4161	0.3740	0.4580
	Vitamin A Deviation (%)	-42.32	-43	43
	Exploration Parameters			
	Amplitude (F)	0.15		
	Probability (CR)	0.85		
	Number of solutions	500		
	Number of iterations	4 000		

1 US$ = 101.81 Kenyan Shillings as at 30/11/2016

Table S4.4: Objectives, decision variables modified, constraints applied and exploration parameters used during the generation of alternative farm configurations for the farms Doan Ket and Na Phuong, Vietnam.

Farm		Original	Min	Max
Doan Ket	**Objectives**			
	Household Free Budget (US$ year^{-1})	2 281		✓
	Nutrient System Yield Vitamin A (capita ha^{-1})	5.2		✓
	Household Leisure time (hours year^{-1})	0		✓
	Vitamin A Deviation (%)	-70.9		✓
	Decision Variables			
	Tree area (ha)	0.7	0	1.07
	Maize + Onion Bulb area (ha)	0.1	0	1.07
	Maize + Spr. Onion + Fr. bean area (ha)	0.15	0	1.07
	Maize + Fr. bean + Maize area (ha)	0.12	0	1.07
	New French bean area (ha)	0	0	1.07
	New Mustard Greens area (ha)	0	0	1.07
	New Water Spinach area (ha)	0	0	1.07
	New Orange Flesh Sweet Potato area (ha)	0	0	1.07
	New French beans to home use (-)	0	0	1
	New Mustard greens to home use (-)	0	0	1
	New Water Spinach to home use (-)	0	0	1
	New Orange Flesh Sw. Potato to home use (-)	0	0	1
	Constraints			
	Ruminant Dry Matter Intake (%)	-25	-999	0
	Ruminant Energy Requirements (%)	0	-5	5
	Total Farm area (ha)	1.07	0.963	1.177
	Exploration Parameters			
	Amplitude (F)	0.15		
	Probability (CR)	0.85		
	Number of solutions	500		
	Number of iterations	4 000		
Na Phuong	**Objectives**			
	Household Free Budget (US$ year^{-1})	1 370		✓
	Nutrient System Yield Vitamin A (capita ha^{-1})	6.5		✓
	Household Leisure time (hours year^{-1})	0		✓
	Vitamin A Deviation (%)	-32.5		✓
	Decision Variables			
	Maize area (ha)	0.35	0	0.5
	Coffee area (ha)	0.02	0	0.5
	Maize + Maize area (ha)	0.15	0	0.5
	Rice + Rice area (ha)	0.09	0	0.09
	New French bean area (ha)	0	0	0.5

Na Phuong	New Mustard Greens area (ha)	0	0	0.5
	New Water Spinach area (ha)	0	0	0.09
	New Orange Flesh Sweet Potato area (ha)	0	0	0.5
	New French beans to home use (-)	0	0	1
	New Mustard greens to home use (-)	0	0	1
	New Water Spinach to home use (-)	0	0	1
	New Orange Flesh Sw. Potato to home use (-)	0	0	1
	Constraints			
	Ruminant Dry Matter Intake (%)	0	-999	0
	Ruminant Energy Requirements (%)	0.5	-5	5
	Total Farm area (ha)	0.64	0.5724	0.6996
	Irrigated fields area (ha)	0.09	0.081	0.099
	Rain-fed fields area (ha)	0.52	0.468	0.572
	Exploration Parameters			
	Amplitude (F)	0.15		
	Probability (CR)	0.85		
	Number of solutions	500		
	Number of iterations	4 000		

1 US$ = 22 665.46 Vietnamese Dong as at 30/11/2016

Table S4.6 Comparisons of the values of selected indicators before generation of alternative farm configurations and the highest value within the generated solution set for the four modelled farms.

	Mambai		Masana	
Indicator	**origin**	**max**	**origin**	**max**
Leisure time (hours yr^{-1})	0	1 876	0	565
Household Free Budget (US$ yr^{-1})	-1 053	-173	-187	159
Farm net income (US$ yr^{-1})	1 312	2 344	1 053	1 589
Gross Margin Crops (US$ yr^{-1})	1 122	2 473	900	1 675
Gross Margin Animals (US$ yr^{-1})	458	651	258	267
Food Costs (US$ yr^{-1})	1 781	2 018	1 269	1 539
Proportion food costs (%)	75	78	87	89
NSYvita (capita ha^{-1} yr^{-1})	39	64	7	26
Animal Nitrogen Use Efficiency (%)	20	28	2	2
Organic Matter added (kg ha^{-1} yr^{-1})	776	1 282	490	556
Nitrogen soil losses (kg ha^{-1} yr^{-1})	98	254	71	83

	Doan Ket		Na Phuong	
Indicator	**origin**	**max**	**origin**	**max**
Leisure time (hours yr^{-1})	0	2 660	0	809
Household Free Budget (US$ yr^{-1})	2 281	2 874	1370	1 798
Farm net income (US$ yr^{-1})	4 864	5 479	3 110	3 536
Gross Margin Crops (US$ yr^{-1})	2 231	4 220	2 258	2 757
Gross Margin Animals (US$ yr^{-1})	3 310	3 891	1 402	1 402
Food Costs (US$ yr^{-1})	1 992	2 186	1 635	1 689
Proportion food costs (%)	71	72	79	79
NSYvita (capita ha^{-1} yr^{-1})	5	36	7	17
Animal Nitrogen Use Efficiency (%)	47	57	22	23
Organic Matter added (kg ha^{-1} yr^{-1})	692	746	832	944
Nitrogen soil losses (kg ha^{-1} yr^{-1})	193	403	327	323

1 US$ = 101.81 Kenyan Shillings and 1 US$ = 22 665.46 Vietnamese Dong as at 30/11/2016.

Table S4.5: Dietary Reference Intakes (DRI) values: (70% of Recommended Nutrient Intake) used in FarmDESIGN (Otten *et al.*, 2006, Kujinga *et al.*, 2017, de Jager *et al.*, 2019, Samuel *et al.*, 2019)

Gender	Age	Status	Energy	Mg	Ca	Fe[4]	Zn[4]	Thiam.	Ribofl.	Folate	Niacin	Vit. A	Vit. B-6	Vit. B-12	Vit. C
	years		kcal	mg	mg	mg	mg	mg	mg	µg	mg	µgRAE	mg	µg	mg
Child	0.5	Normal	399	21	147	0	6.6	0.14	0.21	45.5	1.4	280	0.07	0.28	28
Child	1	Normal	518	52.5	189	13.8	8.4	0.21	0.28	56	2.8	350	0.21	0.35	35
Child	3	Normal	861	56	350	10.8	6.9	0.35	0.35	105	4.2	210	0.35	0.63	10.5
Child	8	Normal	1200.5	91	560	14.8	9.3	0.42	0.42	140	5.6	280	0.42	0.84	17.5
Male	13	Normal	1596	168	910	20.9	14.3	0.63	0.63	210	8.4	420	0.7	1.26	31.5
Male	18	Normal	1928.5	287	910	26.9	14.3	0.84	0.91	280	11.2	630	0.91	1.68	52.5
Male	30	Normal	1785	280	700	21.1	11.7	0.84	0.91	280	11.2	630	0.91	1.68	63
Male	50	Normal	1785	280	700	21.1	11.7	0.84	0.91	280	11.2	630	0.91	1.68	63
Male	70	Normal	1785	294	840	21.1	11.7	0.84	0.91	280	11.2	630	1.19	1.68	63
Male	120	Normal	1785	294	840	21.1	11.7	0.84	0.91	280	11.2	630	1.19	1.68	63
Female	13	Normal	1449	294	910	17.5	12	1.33	0.63	210	8.4	420	0.7	1.26	31.5
Female	18	Normal	1477	168	910	28.4	12	0.7	0.7	280	9.8	490	0.84	1.68	45.5
Female	30	Normal	1358	252	700	29.2	8.2	0.77	0.77	280	9.8	490	0.91	1.68	52.5
Female	50	Normal	1358	217	700	29.2	8.2	0.77	0.77	280	9.8	490	0.91	1.68	52.5
Female	70	Normal	1358	224	840	14.1	8.2	0.77	0.77	280	9.8	490	1.05	1.68	52.5
Female	120	Normal	1358	224	840	14.1	8.2	0.77	0.77	280	9.8	490	1.05	1.68	52.5
Female	18	Pregnant	1895.6	280	910	110	12.5	0.98	0.98	420	12.6	525	1.33	1.82	56
Female	30	Pregnant	1895.6	245	700	110	12.5	0.98	0.98	420	12.6	525	1.33	1.82	59.5
Female	50	Pregnant	1895.6	252	700	110	12.5	0.98	0.98	420	12.6	539	1.33	1.82	59.5
Female	18	Lactating	1925	252	910	21.4	14.1	0.98	1.12	350	11.9	840	1.4	1.96	80.5
Female	30	Lactating	1925	217	700	21.4	14.1	0.98	1.12	350	11.9	910	1.4	1.96	84
Female	50	Lactating	1925	224	700	21.4	14.1	0.98	1.12	350	11.9	910	1.4	1.96	84

4. Values for iron and zinc were taken from the Estimated Average Requirements (EAR) of the WHO (2005) and adjusted for low bioavailability of these nutrients in smallholder diets (Fe 5% and Zn 15% bioavailability).

Chapter 5
Strategies steering managerial intensification pathways of farmers in Central Malawi

Carl Timler, Jeroen C. J. Groot, Sieglinde S. Snapp and Pablo Tittonell

◀ Malawian farmer inspecting her maize. Photo: Niel Palmer, CIAT

Abstract

Smallholder farmers in Malawi face many challenges to improving their livelihoods and food security. Intensification of agricultural production is an option to achieve these goals. Yet farmers are highly heterogenous in their strategies towards intensification. This study uses Q Methodology to ascertain the different perspectives of smallholder farmers in Central Malawi regarding their desire to develop their farm along various managerial intensification pathways (MIPs). We find evidence for three main strategies which we have named: Aspirant Modern Farmers, Seed Saving Peasants and Entrepreneurial Business(wo)men. These were linked to four different hypothesized MIPs. Aspirant Modern Farmers willingly adopt hybrid seeds and inorganic fertilizers but require more extension support; these farmers follow a technology-oriented MIP. Seed Saving Peasants focus strongly on local seed systems and post-harvest protection of grains, but would also allocate more labour to improving crop residue use and manure quality, thus pointing to a labour-oriented MIP. Entrepreneurial Business(wo)men are early adopters of new technologies and benefit from improved access to market information and suppliers of new technologies. These three strategies did not significantly correlate with structural farm features, which might indicate that the various perspectives are independent of the level of resource endowment of farmers. We conclude that semi-quantitative assessment of farmer aspirations and strategies could provide complementary information to structural farm typologies to support the pathways of sequential innovation decisions of farmers towards sustainably intensified farms.

5.1 Introduction

Smallholder farmers manage a large proportion of the agricultural land globally, and produce much of the food that is consumed (Samberg *et al.*, 2016). Therefore, they are considered as being a crucial category of producers contributing to securing future food supply for a growing global population (Kamara *et al.*, 2019). Simultaneously their livelihoods (income, nutrition, equity) should be improved. Smallholder farmers often aim to combine producing food, fuel and fibres for subsistence with generating income from sales of crop or animal products from their farms. (Valbuena *et al.*, 2014) Farm performance regarding both objectives can be improved by efficiently increasing the production volume. The production volume can be increased by expanding the farm area (extensification), but, in Malawi, there are land availability constraints due to the increasing population density (Potts, 2006; Ricker-Gilbert *et al.*, 2014). Peter *et al.*, (2018) state that, in Malawi's recent past, extensification had occurred, however options for any further extensification in Malawi were limited to protected or marginal areas unsuitable for production. Thus the remaining option is for farmers to attempt to intensify their agricultural production. Options for intensification are to i) produce mixtures of crops (intercropping), or other crops or animal species that are more productive or nutritious, ii) cultivate the same area of land multiple times per year when biophysical conditions and input availability allow, or iii) boost the productivity of individual crops by increasing inputs levels, improving management practices and reducing yield-limiting factors. (Mungai *et al.*, 2016; Snapp *et al.*, 2018)

Farm productivity and attempts to intensify production are mediated and influenced by three important factors: biological processes and natural resources that support production, external inputs and technologies that are used, such as seeds, fertilizers, pesticides, feeds, veterinary care, machinery, etc., and the quantity and quality of labour for management of crops and animals. These factors, represented by natural capital, manufacturing capital and labour respectively in Figure 5.1, interact. For instance, more skilled and knowledgeable labour input can contribute to better management of the natural resources and more efficient use of inputs. Greater focus on improvement of natural capital can enhance nutrient cycling and bio-control on the farm, hence reducing the need for external inputs.

We hypothesize that, from a farm management perspective, the main entry points for intensification are through the quantity and quality of labour (labour-based intensification) and the utilization of inputs and technologies (technological intensification) (Van der Ploeg, 2013), and that on the basis of the interactions among the production factors, four conceptual managerial intensification pathways (MIPs) can be distinguished. The first pathway of

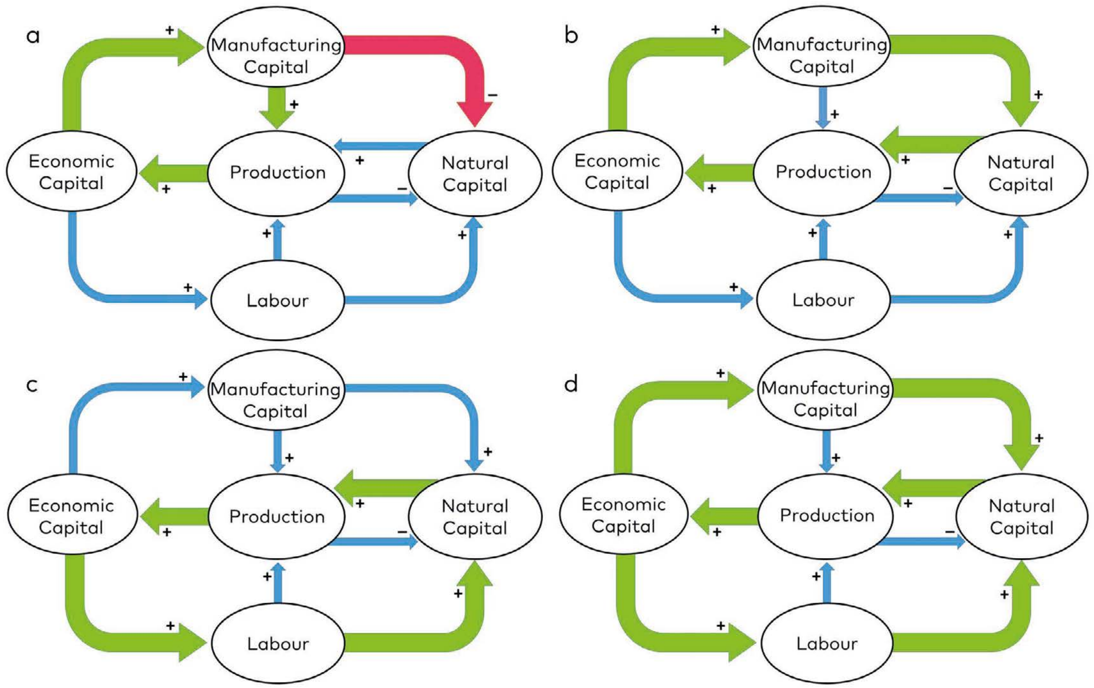

Figure 5.1 Hypothesized managerial intensification pathways: (a) technological intensification (TI) based on high levels of artificial inputs disregarding natural capital, (b) sustainable technology-based intensification (STI) based on technologies enhancing natural capital, (c) labour-based intensification (LBI) based on labour and enhancing natural capital, and (d) integrated techno-ecological intensification (TELI) as a combination of technology- and labour-based intensification greatly enhancing natural capital. Thicker green (positive) and orange (negative) arrows designate dominant interactions, while thin blue arrows designate processes that are less dominant.

technological intensification (TI) can be primarily based on technologies that have short-term benefits but reduce the natural capital of the farm over the longer term (Figure 5.1a), or can be more sustainable (STI) by using the technologies and practices to build and protect natural resources in both the short and long term (Figure 5.1b). Alternatively, a labour-based intensification pathway (LBI) mostly seen in peasant farms is essentially focusing on limiting input use (economical farming) and strengthening biological processes to improve production over time (Figure 5.1c). As a final strategy, an integrated techno-ecological intensification pathway (TELI) that uses aspects of sustainable technological intensification (Figure 5.1b) and labour-based intensification (Figure 5.1c) could be envisioned for both short and long term improvements in production (Figure 5.1d). The rates at which these effects influence the three capitals can vary, potentially encouraging farmers to choose pathways that provide quicker returns, rather than those with slower rates of improvement.

Insight in the intensification pathways is essential to establish the requirements of farmers to improve the productivity of their enterprises and to anticipate the potential impacts of farm development on socio-economic and environmental dynamics. Farming systems are highly heterogeneous with different biophysical conditions, market access and family stage and aspirations (Alvarez *et al.*, 2018). An intensification pathway provides a dynamic perspective on this diversity and farmer requirements in terms of inputs, information and other support. Although the need for intensification is widely articulated there are large concerns over the sustainability of agriculture, due to high levels of inputs and inefficient use of these inputs that results in degradation of natural resources, environmental pollution and consequently overshooting of planetary boundaries (Rockström *et al.*, 2017). Therefore, there is a strong incentive to develop strategies and pathways that are more sustainable (Pretty *et al.*, 2011).

Farmers adapt and improve their farm enterprise to better meet their aspirations within contextual constraints and influences that are shaped by the availability of farm resources, the biophysical environment and the socio-economic conditions and policies. The sequence of adaptations is based on strategic choices. A strategy can be understood as an approach that affects the farm as a whole, is informed by long-term objectives and governs the selection of practices and technologies (cf. Ackoff, 1990). We assume that a coherent strategy shapes the farm development pathway or trajectory. The objectives of this study were to inventory if farmers have different strategies regarding farm improvement and intensification, and whether these strategies could be associated to coherent sequences choices as expressed in the four hypothesized managerial intensification pathways. We analyze these strategies and intensification pathways among smallholder farmers in Central Malawi who combine subsistence and entrepreneurial objectives, face the dual constraints of land and input scarcity and who are in urgent need of further development of their farms and improvement of their livelihoods.

5.2 Methodology

The four hypothesized MIPs (Figure 5.1) including hypothetical examples were presented to a panel of experts in the field of Malawian smallholder agriculture to gather their views on how well these intensification pathways matched reality. Q Methodology (Stephenson, 1935; Watts & Stenner, 2005) was used to gather the opinions of the farmers. A set of statements, known as a Q-set, was generated and was presented to the panel of experts. These statements were all related to the four MIPs, the perceived opportunities and constraints, and the likely order of implementation, of novel intensification technologies and practices. The expert panel, together with the researchers edited the statements until no more changes were suggested. The ratio between the final number of statements and participants is recommended to be at least 1:1 and for statistical reasons there should be fewer participants than statements (Watts & Stenner, 2005). Forrester *et al.* (2015) concurringly remark that most researchers agree that it is beneficial to have more statements than respondents, however, some recent studies such as Nordhagen *et al.* (2017) and Zabala *et al.* (2017) have had fewer statements than respondents.

The study sites were in Central Malawi in the Dedza and Ntcheu Extension Planning Areas (EPAs). In each EPA, two districts were chosen, Linthipe and Golomoti in Dedza and Nsipe and Kandeu in Ntcheu. Structural and functional farm and household data from 75 farmers from the four districts, collected in April 2014 and January 2015 using semi-structured surveys, was used to select the farmers to perform the Q Methodology. Farm households were initially sampled (April 2014) using a Y-frame method (Tittonell *et al.*, 2013) from pairs of villages in each district. Each village pair consisted of a project intervention and non-intervention site. Equal numbers of farmers from the four districts were selected for the Q methodology study. The farmers were selected such that the selected population had farmers with a range of land sizes, incomes, expenditures and livestock numbers. A total of 40 farmers were selected.

The final 52 statements (in English and translated into Chichewa) were printed onto cards. A grid, as shown in Figure 5.2, was used to arrange the sorted cards. In this grid, the participants were forced to arrange the statements according to the strength with which they agreed or disagreed with the statements. The participants initially sorted the cards into three piles namely; 'agree with', 'disagree with' and 'neutral'. Then they gradually worked through the two non-neutral piles to divide them further into three (or more) piles, arranging the printed cards on the grid. Illiterate respondents needed the statements read out aloud to them. Nordhagen *et al.* (2017) found no differences between the results of literate or illiterate respondents. Malia and Bennett (2011) indicate that the presence of the researcher during the Q-sort could unconsciously influence the participant's responses though.

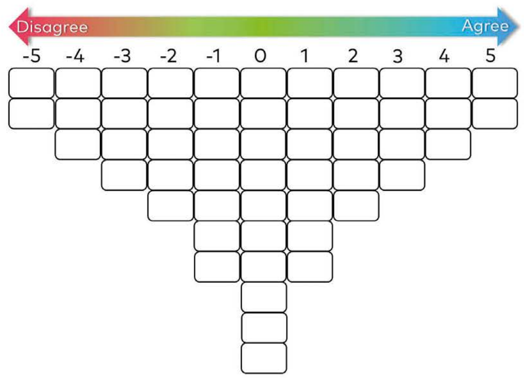

Figure 5.2 Quasi-normal distribution table used for Q-sorting.

Each Q-sort was followed by post-hoc questioning to discover any errors or misunderstandings, and to get a deeper understanding of the participant's reasons for sorting the statements as they did. The post-hoc interviews were also later used to affirm the results from the statistical analysis.

After the Q-sorts were performed, a matrix was composed of the statements (rows) and the different Q-sorts (columns). This matrix was used in the statistical analysis which was performed in the R environment using the package qmethod (Zabala, 2014).

The analysis used the call `qmethod()` to produce the statistical results; Q-sort factor loadings, flagged Q-sorts, statement z-scores, statement factor scores, general factor characteristics (average relative coefficients, number of Q-sorts loading per factor, eigenvalues, explained variance, reliability and standard error of the f-scores), correlation between factor z-scores, standard error of differences between factors and finally the distinguishing and consensus statements per factor. This analysis was performed with varying numbers of factors and a final choice was made with regard to how many factors to use.

The statements that were distinguishing for each factor informed the narrative for the various opinions regarding sustainable intensification of the farmers. The loadings of these statements were aggregated and mapped onto the representation of the discourse (Figure S5.1). The results of the Q methodology were qualitatively described by these narratives, and indicated which types of farmers hold which notions and thus which managerial intensification pathway they would follow. This was a partly inductive approach, but was supported by the fact that during the construction of the concourse these pathways were used as reference material for the formulation of many statements. Some further challenges encountered during execution of this methodology were the discovery of a slightly mis-translated statement and that, during the creation of the concourse of statements, the panel of experts could have been more diverse.

5.3 Results

Correlations among the Q-sorts were analysed using the Pearson method (Figure 5.3). There was high correlation between the Q-sorts Q32 to Q40. These were all performed in the Linthipe EPA in Dedza district and reflected that these farmers had similar perspectives on similar statements. There was poor correlation between the three Q-sorts; Q05, Q07 and Q19, and almost all other Q-sorts indicating that these farmers differed in their perspectives to all other sampled farmers.

5.3.1 The number of factors

There are a number of characteristics that can be examined in order to choose the number of factors to use; eigenvalues that are greater than one, the explained variance of the factors, the number of flagged Q-sorts per factor and the number of unflagged[1] Q-sorts. These characteristics are presented in Table 5.1.

Due to there being more unflagged Q-sorts, lower eigenvalues and less explained variance using four factors, than when using three factors, it was decided to perform the analysis using three factors. In the following section the factors will be described with regard to the statements that distinguish them.

1. Unflagged Q-sorts have no clear affiliation to one factor, rather have opinions belonging to more than one factor.

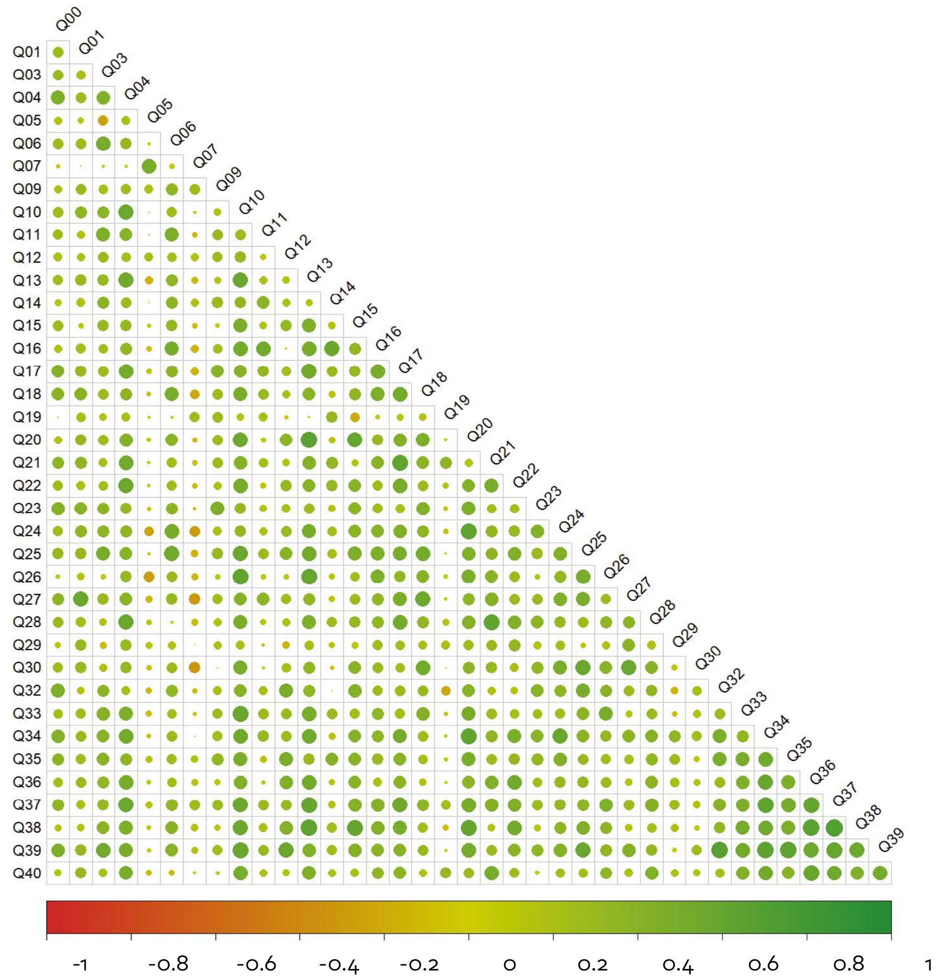

Figure 5.3 Correlation heatmap of the Q-sorts performed in Dedza and Ntcheu, Central Malawi, June 2017. Size of circles and their colour indicate the strength and direction of the correlations.

5.3.2 Factor Descriptions

On the basis of the calculated z-scores, all the statements and their factor scores are presented in Table S5.1. This indicates the arrangement of the Q-sort typical to a respondent belonging to each factor. To distinguish between the factors the distinguishing statements for each factor are presented in Table 5.2. Distinguishing statements have significantly different z-scores (cf. Figure S5.2).

Table 5.1 Differences in a number of characteristics relating to the analysis of the Q-sorts with three, or with four factors.

General Factor characteristics	Number of factors = 3	Number of factors = 4
Number of Q-sorts loading		
Factor 1	16	15
Factor 2	11	7
Factor 3	7	4
Factor 4		3
Number of unflagged Q-sorts	4	9
Eigenvalues		
Factor 1	8.3	7.8
Factor 2	5.1	5.1
Factor 3	4.4	4.1
Factor 4		3.1
Explained Variance		
Factor 1	22.0	20.5
Factor 2	13.0	13.4
Factor 3	11.0	10.8
Factor 4		8.2

Table 5.2 Distinguishing statements for each factor. Numbers to the left of each statement indicate the factor scores for each statement for each factor, indicating the typical score a respondent belonging to that factor would have chosen for that statement. Scores range from 5, very strongly agree, through 0, which is neutral, to -5, which is very strongly disagree.

'Aspirant Modern Farmers'		'Seed Saving Peasants'		'Entrepreneurial Business(wo)men'	
4	To produce more food I only need to use more fertilizer	5	Saving seeds to replant them the following season is a good strategy for me to save money	1	Hiring extra labour means I can work less
3	A lack of access to extension prevents me from making any changes in the way I farm	2	Using PICS grain storage bags is something I would do to reduce post-harvest losses	1	Using post-harvest storage chemicals (like Actellic) is something I would do to reduce post-harvest losses
3	I think that hybrid maize seed is a good way to produce more food or earn more money	2	I think that digging a pit for manure storage and building a roof over it, is worth the labour and material costs it requires as the manure will have better quality	-1	I would plant Orange Fleshed Sweet Potatoes on my farm
0	A lack of (family) labour prevents me from making any changes in the way I farm	1	I would invest extra labour to incorporate maize residues into the soil because it improves the soil quality	-1	If I earned money from non-farm work I would invest it in my farm
0	Growing doubled up legumes (e.g. Groundnuts and Pigeon peas planted together in the same field) is something I would do	0	If I have no money to invest in my farm, I will work on other farms	-2	Spending more of my time weeding (more than what I already do), is something I would do to improve yields

Table 5.2 Continuation

'Aspirant Modern Farmers'		'Seed Saving Peasants'		'Entrepreneurial Business(wo)men'	
-2	Keeping pigs would be a good business to run and is something I would do	-2	I would rather plant local maize varieties than hybrid maize varieties		
-4	If I produced more maize, I would rather sell it, than use it to feed my family	-4	Investing my money in buying new hybrid maize seed every year is something I would do		
-5	Planting a crop like tobacco to sell for cash is a better way to ensure food security than growing a food crop	-5	I would rather burn my maize residues than incorporate them into the soil as this saves me labour		

Factor 1 – "Aspirant Modern Farmers"

The farmers who held this opinion strongly agreed that they want their children to take over their farm. To some degree, this is a cultural characteristic of all these smallholder farmers (but particularly of the farmers in the Linthipe district). Their strong feelings towards this statement were also reflected in comments in their post hoc interviews where they stated a desire to look after the land so that their children would not inherit degraded lands, nor have to struggle to find land to cultivate. This viewpoint was also reflected in the other strongly agree (+5) statement, *"I would invest extra labour to incorporate maize residues into the soil because it improves the soil quality"*. In turn, this viewpoint was still further strengthened with a strong disagreement (-5) with statement 15, *"I would rather burn my maize residues than incorporate them into the soil as this saves me labour"*. Their disagreement (-3) with statement 25, *"If I have no money to invest in my farm, I would look for a non-farming job"*, showed their attachment to, and desire to work on and improve, their own farm.

These farmers indicated not being particularly labour-constrained. This was shown by statement 3, *"A lack of (family) labour prevents me from making any changes in the way I farm"*, which was a neutral and distinguishing statement for factor 1. However, their disagreement (-3) with statement 10, *"Hiring extra labour is not something I want to do"* indicated they would not be averse to hiring extra labour. They are diligent, and place importance on timely cultivation practices and the use of purchased inputs such as hybrid seeds, fertiliser and (broad spectrum) insecticides. This was reflected by the scores of +4 for statements 13, *"I usually try to improve my harvest by working hard to plant and weed carefully and on time"*, 21, *"To produce more food I only need to use more fertilizer"* and 36, *"Using post-harvest storage chemicals (like Actellic) is something I would do to reduce post-harvest losses"*, and scores of +3 for statements 33, *"I think that hybrid maize seed is a good way to produce more food or earn more money"* and 32, "*Investing my money in buying new hybrid maize seed every year is something I would do*". However, they felt challenged, or held back by a lack of extension; statement 5 *"A lack of access to extension prevents me from making any changes in the way I farm"* being a distinguishing statement for this factor. They were also distinguished by their neutral feelings towards statement 44, *"Growing doubled up legumes (e.g. Groundnuts and Pigeon peas planted together in the same field) is something I would do"* reflecting a lack of interest in adopting this innovation widely promoted by the AfricaRISING project.

The "Aspirant Modern Farmers" would be adverse to planting only a cash crop and purchasing food with the profits, shown by their strong disagreement (-5) with the distinguishing statement 41, *"Planting a crop like tobacco to sell for cash is a better way to ensure food security than growing a food crop"*, and their disagreement (-4) with the distinguishing statement 42, "If I produced more maize, I would rather sell it, than use it to feed my family" as well as statement 43, *"I prefer to sell my farm products and buy food for my family rather than produce our own food"*. They were further distinguished by their disinterest in keeping pigs as a business as shown by their disagreement (-2) with statement 28, *"Keeping pigs would be a good business to run and is something I would do"* when compared to the positive scores for this statement from the other two factors.

Factor 2 – "Autonomous Seed Saving Peasants"

The farmers who held this opinion strongly agreed (+5) that saving seeds would be a good strategy for saving money and their strong viewpoint on statement 31 *"Saving seeds to replant them the following season is a good strategy for me to save money"* distinguishes them from the other two factors. Furthermore, they disagreed (-4) with statement 32 *"Investing my money in buying new hybrid maize seed every year is something I would do"* indicating their unwillingness to have to purchase hybrid maize seeds annually. Additionally, that fact that statement 30, *"I would rather plant local maize varieties than hybrid maize varieties"* was distinguishing for this factor, and that they disagreed less than the other two factors with this statement further strengthened their viewpoint about their desire for autonomy regarding seed self-sufficiency. The fact that, in the rural areas of central Malawi, (hybrid) seeds are usually not available on time or are sold out at planting time is a strong driving force for these farmers to want to save seed. Having their own seed allows them to plant at precisely the right time.

They strongly agreed (+5) that mineral fertilizers are better than compost or manure. For statement 18, *"Mineral fertilizer is better than animal manure or compost for improving the fertility and quality of my soil"*, each factor had a significantly different viewpoint. They furthermore, would be prepared to work harder to achieve their goals as shown by the strength of their agreement (+4) for statements 7, *"If I have no money to invest in my farm, I will work more/longer hours on my farm to achieve better yields"* and 13, *"I usually try to improve my harvest by working hard to plant and weed carefully and on time"* and their disagreement (-4) with statement 3, *"A lack of (family) labour prevents me from making any changes in the way I farm"*. They were distinguished by their neutrality on statement 23, *"If I have no money to invest in my farm, I will work on other farms"* showing that they had no desire to invest their labour on other's farms.

The "Autonomous Seed Saving Peasants" strongly disagreed (-5) with statement 15, *"I would rather burn my maize residues than incorporate them into the soil as this saves me labour"* (as do all factors), however for this factor, it was a distinguishing statement. Agreement (+2) with the distinguishing statement 19, *"I think that digging a pit for manure storage and building a roof over it, is worth the labour and material costs it requires as the manure will have better quality"* indicated some interest from this factor in adopting innovations regarding the building of improved manure storage systems and more efficient use of on-farm produced organic resources. During post-hoc interviews, farmers asked for more detailed descriptions of such structures, as well as indicated a desire to be taught how to construct them.

They disagreed strongly (-5) with statement 43, *"I prefer to sell my farm products and buy food for my family rather than produce our own food"*, however, conversely also disagree (-3) with statement 51, *"I would rather eat the vegetables I produce, than sell them to buy other food"*. This can be explained by the interpretation of *"farm products"* by the respondents to only mean maize, and that fact that maize is traditionally viewed as a crop that you would only keep to eat, whereas vegetables are perishable, temporarily in oversupply, and are hence used to generate income.

Their agreement with the statement regarding using PICS[2] storage bags distinguished them from the other two factors. Farmers who were interested in these bags, saw the benefits in the re-usability of the bags despite their higher initial investment costs. Some also desired to use less chemicals. These viewpoints further indicated their desire for reducing their dependence on external inputs.

Factor 3 – "Entrepreneurial Business(wo)men"

The farmers with this opinion agreed strongly (+5) with statement 12, *"Purchasing herbicide to kill weeds makes sense because it would save me labour"*, and statement 39, *"Buying a treadle or motorized pump to irrigate my crops is a good investment of my money"*. Both these viewpoints indicated a more entrepreneurial, business-like approach to farming. This was further supported by the agreement (+4) with statements 28, *"Keeping pigs would be a good business to run and is something I would do"* and 24, *"If I have no money to invest in my farm, I will attempt to take out a small loan or sell my livestock"*. The majority of the farmers in this group would be regarded as well resource endowed farmers, and included the farmers with larger numbers of tropical livestock units (TLU's). The agreement (+3 and +2) with statements 16, *"I would like to use machines to reduce my labour load"* and 40, *"If I had enough money to purchase a two-wheel tractor, I think that this would be a good investment of my money"* respectively, indicated an interest from these farmers in mechanization. This was further supported by their strong agreement (+5) with statement 39 as mentioned previously. Small scale mechanization was therefore a desired intensification option of the farmers with this strategy.

The "Entrepreneurial Business(wo)men" strongly disagreed (-5) that local maize is better than hybrid maize, indicating their strong preference for hybrid maize varieties which are always purchased annually according to their post-hoc interviews. Some received FISP[3] subsidized hybrid seed and others not. They also disagreed strongly (-5) (as with all other factors) with statement 15, *"I would rather burn my maize residues than incorporate them into the soil as this saves me labour"*. Their disagreement (-4) with statement 18, *"Mineral fertilizer is better than animal manure or compost for improving the fertility and quality of my soil"* was significantly different from the other two factors and reflected a more nuanced viewpoint on the longer-term benefits of compost on soil fertility.

2. Perdue Improved Crop Storage bag. https://picsnetwork.org/
3. Farm Input Support Program through which the least resource endowed farmers are provided subsidized access to agricultural inputs like hybrid seeds and fertilizers, although not always in a timely manner.

This group of farmers also disagreed (-4) with statement 48, *"I would include a doubled-up legume crop (where two bean-like plants are intercropped) on a third of my fields"*, and in some of the post-hoc interviews it was mentioned specifically that the combination of pigeon pea and groundnut was not favourable. Reasons given were that the pigeon pea plants were uprooted during the harvest of the groundnuts. This group was also distinguished by their slight disagreement (-1) for growing orange-fleshed sweet potatoes, compared with neutral viewpoints for other factors.

Regarding their view on labour, a distinguishing statement agreed with (+1) by this group was statement 9, *"Hiring extra labour means I can work less"*. In combination with their agreement (+4) with statement 46, *"I would invest extra labour to incorporate maize residues into the soil because it improves the soil quality"*, and the agreement (+3) with statement 8, *"If I made extra money selling crops, I would consider hiring labourers to do extra work (e.g. weeding or land preparation) on my farm"*, indicated that they have the means and the preference to hire labourers. This was supported further by their disagreement (-2) with the distinguishing statement 11, *"Spending more of my time weeding (more than what I already do), is something I would do to improve yields"* and disagreement (-2) with statement 10, *"Hiring extra labour is not something I want to do"*.

There were two distinguishing statements that were somewhat incongruous with a business-like farmer. Statement 36, *"Using post-harvest storage chemicals (like Actellic) is something I would do to reduce post-harvest losses"* is only slightly agreed with (+1) by this factor, compared with much stronger agreement (+4) and (+3) from factors one and two respectively. This might indicate a desire to use other options to reduce post-harvest losses, yet statement 34, *"Building an improved granary is something I would do to reduce post-harvest losses"*, and statement 35, *"Using PICS grain storage bags is something I would do to reduce post-harvest losses"*, were also only slightly disagreed with (-1) and neutral respectively. This possibly indicated that they did not perceive post-harvest losses to be a major challenge. The other incongruous, yet distinguishing statement, was statement 26, *"If I earned money from non-farm work I would invest it in my farm"*, with which they slightly disagree with (-1). It would seem to make more sense for a business-minded entrepreneurial farmer to have agreed more strongly with this statement. However, it could also indicate that they did not perform off-farm work, earning enough through their own farm business.

In Figure 5.4 we present the individual Q-sorts clustered according to their loadings for the three factors. Two Q-sorts flagged as factor 3 (blue) were not clustered with the others. These two farmers are Q5 and Q7, which were not correlated well with other Q-sorts (Figure 5.3). These two farmers were not typical well-endowed farmers when compared to other farmers in this cluster.

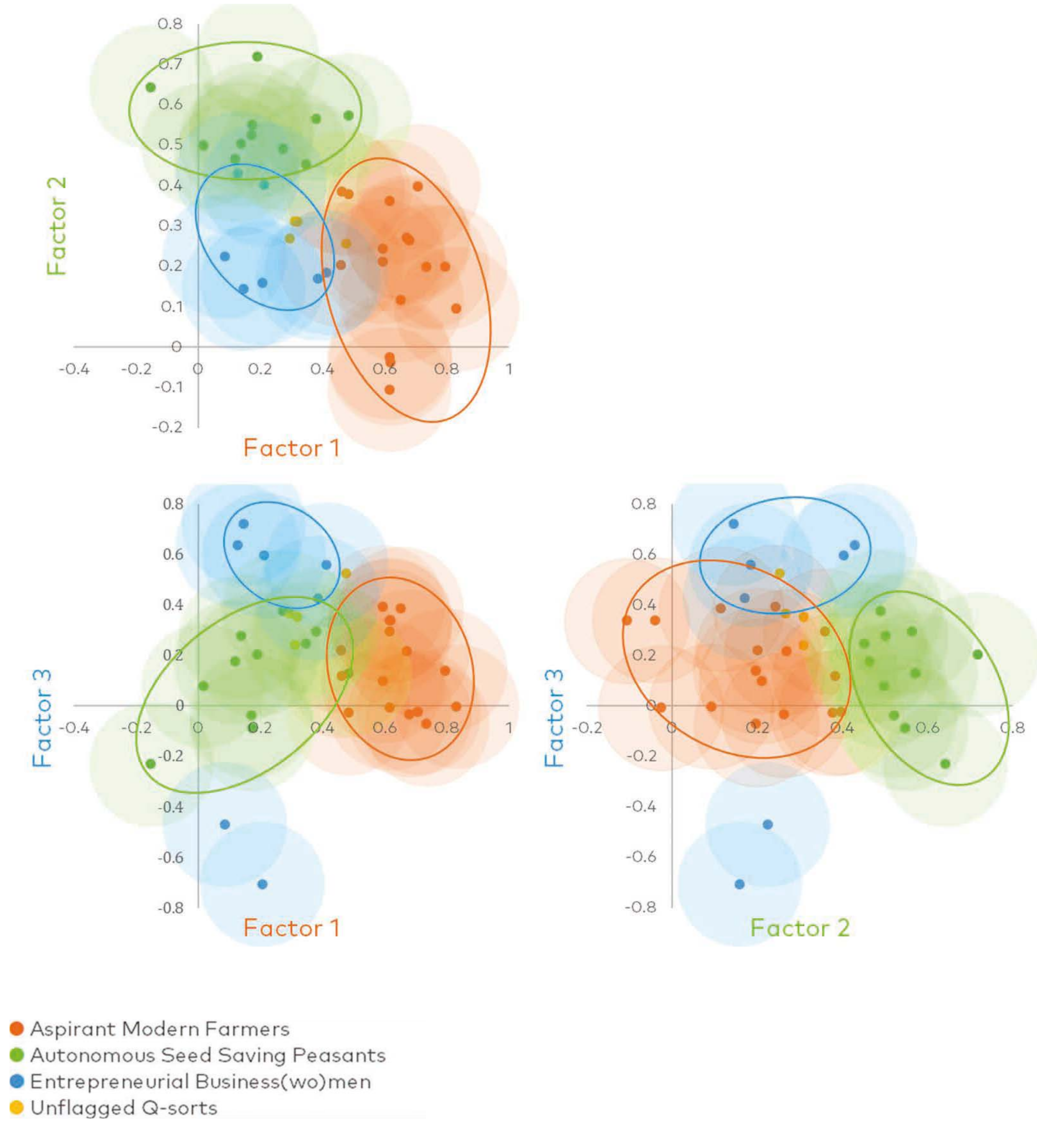

Figure 5.4 Q-sorts displayed according to their loadings for the three factors. Ellipses around clusters of points are hand drawn.

Their views on the distinguishing statements were diametrically opposed to those of others who are clustered in this factor.

The Q methodology discourse statements were mapped onto the representation of strategies (Figure S4.1). In Figure 5.5, the average factor scores are indicated in this mapping for the three Q factors. Some of the major trends we can observe are the following. All factors would prefer to grow their own food to improve their food security (red arrow between economic capital and Food security). "Aspirant Modern Farmers" are not labour constrained (labour is neutral), and thus place less importance on technologies to save labour. "Seed Saving Peasants" agree more with using manufacturing capital to increase natural capital hence reducing costs to improve economic capital. "Entrepreneurial Business(wo)men" agree with adopting technologies to save labour, and improvement of economic capital is less reliant on improved natural capital.

5.3.3 Comparison with Farm and Household data

Structural and functional farm and household of farmers allotted to the factors (Table 5.3) showed a numerical trend indicating that that "Entrepreneurial Business(wo)men" had the most favourable financial indicators, the highest gross margin, off-farm income and total income, although these differences were not significant. Furthermore, this trend extended to their numbers of animal units and land sizes, which tended to be larger than the other factors. The high values of standard deviations and the lack of significance of differences indicate a large variability in structural and functional farm features within Q factors. This could indicate that the factors are not strictly related to the endowment levels, and that farmer with a certain endowment level can have different intensification strategies.

5.4 Discussion

The results showed that three distinct opinions were held by the smallholder farmers, which emerged from this statistical analysis; "Aspirant Modern Farmers", "Autonomous Seed Saving Peasants" and "Entrepreneurial Business(wo) men". Although not significantly different, trends for average farm incomes, expenditures, yields and TLUs showed higher values for farmers with the entrepreneurial business(wo)men opinion and lower values for those with the seed saving peasant opinion.

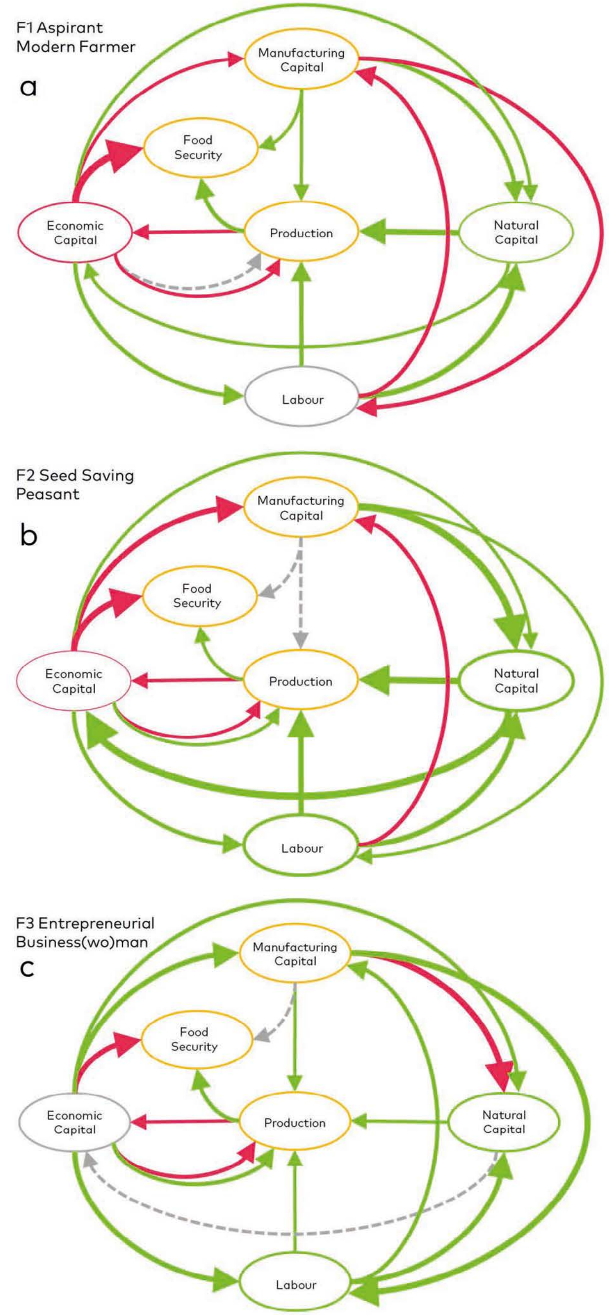

Figure 5.5 Mapping of factor loadings onto relations identified in the Q concourse (see also Figure S5.1 for explanation of the relationships). Red arrows indicate disagreement, green indicate agreement and grey arrows are neutral. The size of the arrow indicates the relative strength of the loading for each relation.

Table 5.3 Averages of farm and household variables (standard deviation in parentheses) for the farmers in the three different factors from semi-structured survey data collected in January 2015.

Variables	Factors: 1 "Modernists" n = 16	2 "Seed Savers" n = 11	3 "Business(wo)men" n = 7
Gross Margin (US$ year^{-1})	200.96 (856.30)	184.48 (233.10)	362.79 (606.10)
Off-farm income (US$ year^{-1})	325.60 (578.68)	284.62 (337.45)	552.81 (803.75)
Total income (US$ year^{-1})	580.34 (942.10)	405.18 (296.96)	862.73 (767.87)
Total Expenditure (US$ year^{-1})	379.38 (289.28)	220.69 (148.39)	499.93 (381.39)
Tropical Livestock Units (TLU)	1.26 (2.10)	0.11 (0.20)	2.31 (3.53)
Yields (kg ha^{-1})	1211 (1127)	997 (531)	2023 (2584)
Land owned (hectares)	2.09 (1.78)	2.32 (1.23)	3.27 (3.43)
Land farmed (hectares)	2.06 (1.58)	2.25 (1.18)	3.28 (3.37)
Land allocated to food crops (hectares)	1.69 (1.43)	1.66 (0.82)	2.29 (1.82)
Land allocated to cash crops (hectares)	0.37 (0.43)	0.60 (0.45)	1.04 (1.56)

These opinions could be linked to the four management intensification pathways presented in Figure 5.1. Farmers of the 'Aspirant Modern Farmer' opinion would correspond to either the TI or STI pathways (Figures 5.1a, 5.1b, 5.5a and 5.5b). These farmers, although wanting to maintain or improve the quality of their lands for their children, also stated a desire to be modern farmers who use modern agricultural inputs. Adopting (or partly adopting) these intensification technologies could possibly reduce their natural capital, for instance, continued use of chemical fertilizers without organic matter inputs could cause deterioration of soil quality. Their neutral opinion towards legume diversification in statements 44 and 48 and investing labour in application of manure in statement 17 (Table S5.1) show that farmers of this opinion would most likely benefit from improved support from extension with advise and demonstrations of environmentally sound practices. This with the aim of directing these farmers more towards the STI than the TI pathway. Ricker-Gilbert and Jayne (2017) in a survey, found evidence for the complementarity of organic inputs and inorganic fertilizers (e.g. legume integration, manure incorporation and conservation agriculture) as means to increase fertilizer cost effectiveness, profitability and sustainability. Further, another survey by Holden and Lunduka (2012) was consistent with the probability and the intensity of manure use by Malawian farmers as being positively correlated to intensity of fertilizer use. This is suggestive that farmers pursuing the Aspirant Modern pathway could adopt hybrid seeds and fertilizer, as desired modern farming techniques, followed by later steps of increased manure use as well as diversifying their rotations with more legumes, reducing tillage and mulching.

Farmers with the "Autonomous Seed Saving Peasant" opinion corresponded to the LBI pathway (Figures 5.1c and 5.5c). They agreed with statements on improving their manure quality by building better manure storage facilities, investing labour in bringing manure to their fields, improving storage using PICS bags and would be more inclined to improve their (poor) financial situation by investing more of their own labour on their own farm, rather than earning money by working on other farms. These are consistent with the trajectory of the LBI pathway. Fisher and Snapp (2014) found that modern maize varieties may be dis-adopted by Malawian farmers due to their dissatisfaction with performance in drought years and poor storability. They highlighted too, the need for seed breeders to consider the opinions of smallholder farmers on traits they find important in modern varieties. For farmers pursuing the pathway of "Seed Saving Peasant", there is need for non-hybrid, improved seeds that allow for the use of saved seed without productivity loss. Due to the relatively weak financial situation of these farmers (Table 5.3), innovations that do not require large financial investments could be initially targeted at these farmers. Transferring knowledge on, for instance, construction methods of improved manure storages would be an example of a first step towards intensification. Thereafter, once such farmers experience improved profits from their improved natural capital, logical next steps might include the purchase of PICS bags for better storage of grains to eat and to sow.

Farmers with the "Entrepreneurial Business(wo)man" opinion corresponded to the STI or TELI pathways (Figures 5.1b, 5.1d and 5.5c). They have greater financial resources (Table 5.3) enabling them to implement new technologies or alternatively, as shown by the two low resource endowed farmers of this notion, (Figure 5.4), be prepared to work harder to implement a new technology. They are not constrained by labour (statement 3 in Table S5.1) and would likely be early adopters and exemplar demonstrators of these new technologies. For farmers with this opinion, providing them with access to better information regarding markets for their products can help in improving their economic capital. With improvements in their economic capital, the provision of access to providers of mechanization options could be a logical next step towards intensification. Improved animal husbandry support as well as initiatives to facilitate access to improved breeds would additionally be steps that farmers with this notion could take.

Walder and Kantelhardt (2018) performed a Q methodological study with Austrian farmers in order to ascertain their viewpoints towards multifunctional agricultural ecosystems. Their comparable study found four viewpoints indicating that agricultural policies should not use a blanket approach but need to take this diversity of mindsets into account. Similarly, in this study, tailored packages should be made available to farmers with these three opinions.

The Q Methodological approach used in this study can rapidly determine patterns within heterogenous farmer viewpoints on chosen topics. We would recommend to make more use of this technique for targeting interventions for the improvement of smallholder livelihoods as this study has shown Q Methodology to rapidly ascertain the diversity of opinions. Rodriguez-Piñeros *et al*. (2012) demonstrate that such techniques, whereby farmers were directly involved and their opinions ascertained, ensured greater community support from small scale farmers in implementing sustainable forest management plans. Furthermore, there is scope for research into whole-farm modelling of the effects on productivity, nutritional, environmental, social and economic indicators, at a farm level, of the adoption of different suites of innovations, by these three different farmer opinions. Creating three farm models of farmers holding these opinions such whole-farm models can be used with farmers to examine trade-offs and synergies inherent in adopting suites of innovations. Thus such models become discussion tools in cycles of participatory extension.

In this way farmers can make informed decisions, weighing up multiple objectives, when moving on a pathway towards a more ecologically intensive farm configuration.

5.5 Conclusions

We have shown that there are three main strategic opinions common among farmers in these study sites. These three opinions can be linked to the four management intensification pathways using the narratives created using the Q sorts of the three factors . We also showed, by the strength of their agreement or disagreement with different statements, that farmers with different opinions would be likely to adopt certain interventions in a step by step fashion on a trajectory towards a more intensive farming configuration. We can draw the following conclusions about these three opinions.

Aspirant Modern Farmers

- desire to use hybrid seeds and fertilizers
- need effective extension to stimulate effective composting, residue management and legume diversification

Autonomous Seed Saving Peasants

- would be receptive to low cost innovations that involve a knowledge transfer
- would adopt innovations that need to be bought (e.g. PICS bags) at later stages

Entrepreneurial Business(wo)men

- need accurate market related information and access to suppliers of new technologies like mechanization
- can aid in dissemination and demonstration of innovations

That a lack of relation to farm structural features could not be statistically linked to each factor indicates that these features are possibly independent of farmer strategy. Ecological intensification combined with effective extension with baskets of options tailored to farmers strategic opinions is needed to have further improvement of ecological agriculture in central Malawi.

5.6 Supplementary Material

Table S5.1 Factor scores for all statements for each of the three factors using n=3 factors. Distinguishing statements for each factor indicated by **bold** numeral within a lined cell.

	f1	f2	f3	Statements
1	1	0	-2	I want to change the way I farm
2	2	1	0	A lack of cash money to invest prevents me from making any changes in the way I farm
3	**0**	-4	-3	A lack of (family) labour prevents me from making any changes in the way I farm
4	-2	-4	-3	Infertile, unresponsive soils on my farm prevent me from making any changes in the way I farm
5	**3**	0	-1	A lack of access to extension prevents me from making any changes in the way I farm
6	5	2	-2	I want my children to take over my farm
7	0	4	3	If I have no money to invest in my farm, I will work more/ longer hours on my farm to achieve better yields
8	1	2	3	If I made extra money selling crops, I would consider hiring labourers to do extra work (e.g. weeding or land preparation) on my farm
9	-1	-1	**1**	Hiring extra labour means I can work less
10	-3	-1	-2	Hiring extra labour is not something I want to do
11	2	1	**-2**	Spending more of my time weeding (more than what I already do), is something I would do to improve yields
12	-3	3	5	Purchasing herbicide to kill weeds makes sense because it would save me labour
13	4	4	3	I usually try to improve my harvest by working hard to plant and weed carefully and on time
14	0	0	0	The extra labour it takes to cut and bring high quality fodder to feed an animal well, is worth the additional manure (and/or milk) it produces
15	-5	**-5**	-5	I would rather burn my maize residues than incorporate them into the soil as this saves me labour
16	-1	-2	3	I would like to use machines to reduce my labour load
17	0	3	1	Investing my labour in carrying animal manure or compost to my fields is something I would do
18	2	5	-4	Mineral fertilizer is better than animal manure or compost for improving the fertility and quality of my soil
19	0	**2**	0	I think that digging a pit for manure storage and building a roof over it, is worth the labour and material costs it requires as the manure will have better quality
20	1	1	2	I would invest my money to purchase livestock in order to get manure
21	**4**	0	0	To produce more food I only need to use more fertilizer
22	3	4	1	To improve my yields I need to improve the soil quality on my farm
23	-2	**0**	-2	If I have no money to invest in my farm, I will work on other farms
24	-1	0	4	If I have no money to invest in my farm, I will attempt to take out a small loan or sell my livestock
25	-3	-1	0	If I have no money to invest in my farm, I would look for a non-farming job
26	1	1	**-1**	If I earned money from non-farm work I would invest it in my farm
27	-2	-2	0	Improved cow breeds are worth the extra money they require to purchase
28	**-2**	3	4	Keeping pigs would be a good business to run and is something I would do
29	2	1	1	Breeding and selling local chickens is a good source of income and is something I would do
30	-4	**-2**	-5	I would rather plant local maize varieties than hybrid maize varieties
31	1	**5**	0	Saving seeds to replant them the following season is a good strategy for me to save money
32	3	**-4**	2	Investing my money in buying new hybrid maize seed every year is something I would do
33	**3**	1	1	I think that hybrid maize seed is a good way to produce more food or earn more money
34	0	-1	-1	Building an improved granary is something I would do to reduce post-harvest losses
35	-1	**2**	0	Using PICS grain storage bags is something I would do to reduce post-harvest losses
36	4	3	**1**	Using post-harvest storage chemicals (like Actellic) is something I would do to reduce post-harvest losses
37	-3	-1	1	Collecting and transporting water for irrigation of maize is something I would do to ensure better maize growth and yields

	f1	f2	f3	Statements
38	-2	-2	2	Building water harvesting structures (e.g. gutters, pipes, ponds and water tanks) to collect irrigation water is something I would invest my labour and materials into
39	-1	-2	5	Buying a treadle or motorized pump to irrigate my crops is a good investment of my money
40	-1	-3	2	If I had enough money to purchase a two-wheel tractor, I think that this would be a good investment of my money
41	**-5**	-3	-3	Planting a crop like tobacco to sell for cash is a better way to ensure food security than growing a food crop
42	**-4**	-3	-3	If I produced more maize, I would rather sell it, than use it to feed my family
43	-4	-5	-4	I prefer to sell my farm products and buy food for my family rather than produce our own food
44	**0**	-1	-1	Growing doubled up legumes (e.g. Groundnuts and Pigeon peas planted together in the same field) is something I would do
45	2	2	2	To improve the nutrition of my family, I would plant Groundnuts and Pigeon peas for them to eat
46	5	**1**	4	I would invest extra labour to incorporate maize residues into the soil because it improves the soil quality
47	1	0	0	Groundnuts and Pigeon peas are good crops to make money with
48	0	-1	-4	I would include a doubled up legume crop (where two bean-like plants are intercropped) on a third of my fields
49	1	0	0	Reducing post-harvest losses is a good strategy to ensure food security
50	-1	0	-1	Planting vegetables to sell is something I would do to earn extra money
51	0	-3	-1	I would rather eat the vegetables I produce, than sell them to buy other food
52	0	0	**-1**	I would plant Orange Fleshed Sweet Potatoes on my farm

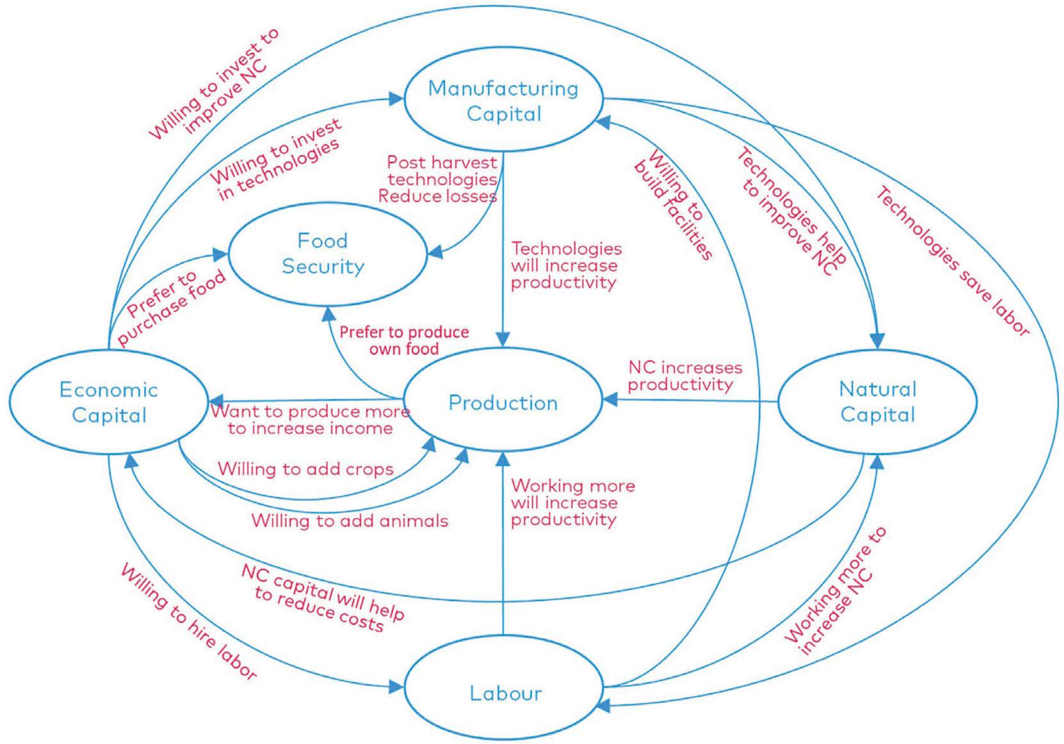

Figure S5.1 The Q methodology discourse statements (see Table S5.1) mapped onto the representation of strategies (see Figure 5.1). NC: natural capital.

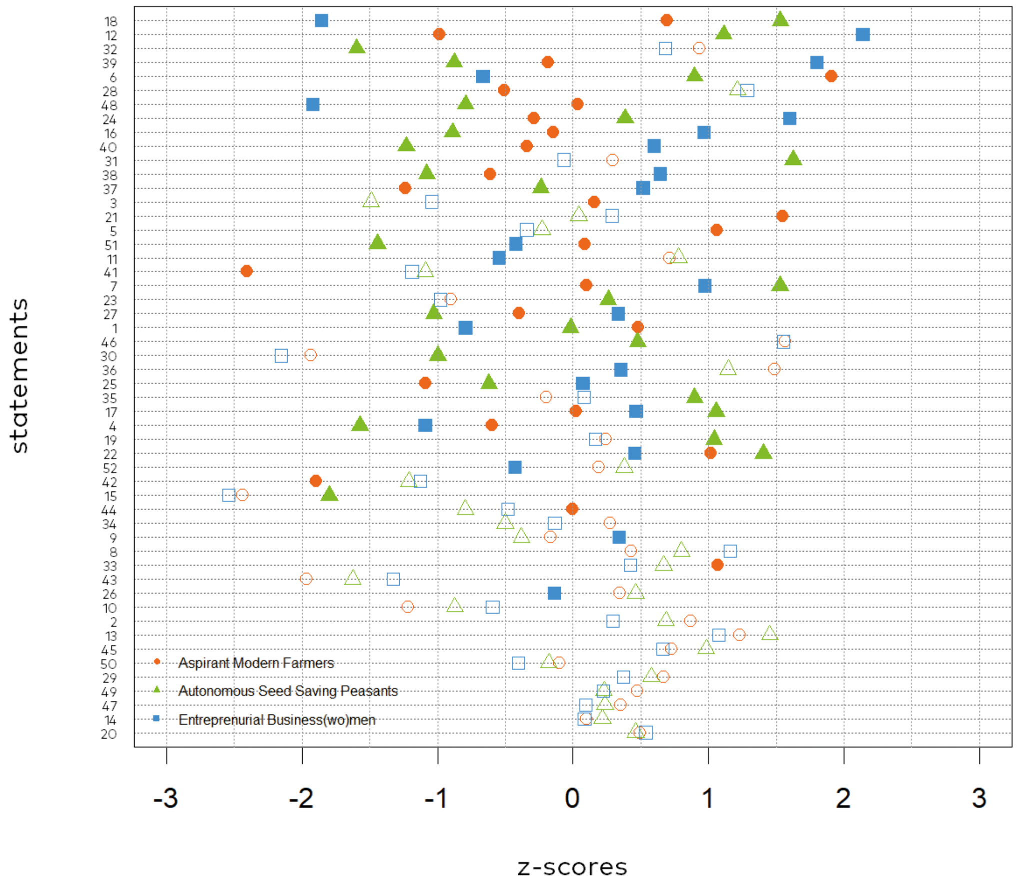

Figure S5.2 z-Scores for all statements for three factors. For each statement; filled points are significantly different, unfilled points are not significantly different, only one filled point indicates a distinguishing statement and three filled points indicate statements which distinguish all factors.

Landscape in Linthipe, Dedza district, Central Malawi in 2017, viewed from the verandah of a typical mudbrick house. Photo: Author's own. ▶

Chapter 6
General Discussion

Carl Timler

◀ Malawian man transporting firewood by bicycle on the road to Lilongwe.
Photo: Mitchell Maher IFPRI

Highlights

- Some sustainable interventions are more suited to certain types of farmers, and the model FarmDESIGN can be used to explore these matches between farmer types and promoted sustainable interventions.
- Q Methodology allows researchers to analyse farmer perceptions and aids in identifying potential trajectories of sustainable intensification.
- Hypothesis-based typologies have to include local stakeholders and experts in the process of creation of hypotheses and validation of typologies.
- Traditional leafy green vegetables can improve farm livelihoods through improved diets and income generation from sales of fresh leaves, even when grown on only small areas of farmland.
- Assessing the diversity of households provides categories to group like-minded farmers together in a participatory focus group setting to discuss their option and challenges and learn from one another aided by output from FarmDESIGN.

6.1 Introduction

Diverse smallholder farmers in Sub Saharan Africa and South Asia are faced with multiple competing objectives with regards to managing their farming systems to ensure adequate nutrition and livelihoods. These farmers also find themselves in population dense areas, often with great resource constraints as a result. Sustainable intensification (SI) can provide opportunities to improve their farm's economic, environmental and nutritional performance and in so doing, their livelihoods (Pretty *et al.*, 2011). There is no shortage of sustainable intensification technologies promoted by various institutes, but which technologies, and in which order of adoption, would which farmers benefit most from, in the farmers' opinions?

In chapter two of this thesis we have shown how datasets from household surveys can be used to create typologies to make sense of the heterogeneity of diverse smallholder farmers in Eastern Zambia (Alvarez *et al.*, 2018). We demonstrated, using five separate typologies, the importance of the formation of a hypothesis using a panel of experts, and how the resulting types can differ when the typology objective differs. We proposed a methodological framework for integrating participatory and statistical methods for hypothesis-based typology construction. Promoted interventions designed by agricultural institutes were tested for different types of farmers identified through the creation of these typologies. We demonstrated this in chapter three, by exploring the suitability of diverse interventions for a range of farm types in Eastern Zambia (Timler *et al.*, 2017). In modelling smallholder households further in chapter four, we made trade-offs and synergies visible, between the multiple competing objectives of farmers in Kenya and Vietnam (Timler *et al.*, 2020). The model output generated solution spaces, and enabled discussions with, and between farmers, to illuminate their way forward towards intensifying their production sustainably. Finally, in chapter five, to assess the diversity of opinions and strategies that these farmers might have and use, we revealed three distinct strategies on sustainable intensification held by farmers in Central Malawi regarding the intensification of their farms. Most of them would aspire to become modern farmers, while two smaller groups of peasants and business (wo)men, rely on their own labour, or desire mechanization and greater market connectiveness, respectively, to intensify their production.

Thus I have used various methods to assess the diversity of smallholder farmers, I have made the trade-offs and synergies between their multiple competing objectives visible using farm modelling and have uncovered their perceptions towards sustainable intensification interventions. In the following sections of this chapter, I discuss the implications of the findings from the previous chapters and how these can be used in combination to describe, explain, explore and design diverse farmer trajectories. Finally, I conclude with my views on sustainable intensification and look to the future of research in this field.

6.2 Making sense of the diversity of farmers through typologies to find matching innovations for diverse farmer types

In my first research question I addressed how to develop and apply methods to analyse and capture the diversity of smallholder farm households, through typology construction, and to determine the effect of different expert hypotheses on farmers' objectives, and of the resulting choice of variable selection would have on the outcome of such methods. We outlined the past wide usage of typologies and the highlighted the importance of choosing indicators with the help of expert panels in chapter two.

We had access to an already collected dataset for Eastern Zambia that we used in Chapters two and three. The large datasets required for a typology are costly and time consuming to create. While statistical typologies based on hierarchical clustering are useful in unravelling the heterogeneity of farming systems other processes of clustering farms and farmers into meaningful groups such as archetypal analysis (Tittonell *et al.*, 2019) are possible. Archetypal analysis uses extremal points, to delineate the main functional features of a sample of farmer's strategies or responses to disturbances, looking for patterns within these responses that can be grouped and used as the basis for a functional typology of these households. The number of farmers needed to be sampled is much lower than traditional typology construction methods shown in chapter two, and as the collection of these variables and farm data takes time and effort, archetypal analysis potentially illuminates a much cheaper and quicker alternative to assessing farmer diversity than using the large datasets required for statistical typologies. Once types of similar farmers have been identified, farm models can be constructed to represent these types.

Agricultural research institutes continually trial new interventions in demonstration field plots, often with state-of-the-art production methods. These demonstrations are presented to farmers, yet farmers do not see these interventions grown in their own fields or under their own management. To address this issue, an approach used in Central Malawi is 'Mother Baby' trials (Snapp, 2002). A central 'Mother' trial plot is planted with examples of a large number of new technologies and subsequently 'Baby' trial plots, with a limited selection of farmer chosen interventions, are replicated by participating farmers on their own fields. This allows farmers to experiment under their own conditions, but still only with a limited selection of innovations. *In silico* modelling of a wide range of interventions for different types of farmers can potentially aid

in the rapid targeting and selecting of promising interventions by researchers and farmers. We demonstrated that the model output allocated different areas of land for each intervention for the farmer types identified using a typology. Especially the medium resource endowed farm types were shown to benefit most from these legume integration interventions. The output from the whole-farm model FarmDESIGN, when used in a participatory setting like a focus group discussion, can aid in generating discussion between farmers regarding the selection of suitable technologies for experimentation that match their farm type.

In all the study sites in this thesis, typologies provided the initial data used to describe the heterogeneity in the farming systems encountered, and informed further research within these communities. As such this method is proven a relevant and essential tool in farming systems analysis.

6.3 Examining the trade-offs and synergies between environmental, nutritional and productive outcomes, assessing diversity at farm level

Smallholder farmers face multiple competing objectives, and these objectives have trade-offs and synergies that are made visible in the output of heuristic algorithms for multi-objective optimization as implemented in the FarmDESIGN model. When, by using objectives set on nutritional yield, and with decision variables set to varying areas of novel crops such as traditional, dark green, leafy vegetables in farming systems, we were able to find solutions in the output that greatly improved the on-farm production of vitamin A from these modelled systems. Even just adding only small areas of these nutrition-sensitive interventions had great effect in closing nutrition gaps. Vitamin A is starkly deficient in the communities I studied, particularly in the most vulnerable population groups, women and young children (WHO, 2009b). For one modelled Kenyan farm, synergies were found between vitamin A yield and farm income by increasing area allocated the vitamin A rich crop kale. Kale is a horticultural crop that can be sold on local markets, however distance to market and ease of access to these markets can possibly constrain such synergies.

I would propose that these synergies should be further supported by enabling shorter value chains for these perishable leafy vegetables, as these farmers can possibly sell excess produce locally or even further away in these shortened value chains. An example of such support systems is the Agricultural Commercialization Clusters with smaller Farmer Production Clusters promoted by The Ethiopian Agricultural Transformation Agency (EATA, n.d.). In these shorter value chains farmers directly benefit financially from being connected to traders. Other solutions are, for example the use of community currencies like Bangla-Pesa. Bangla-Pesa is a secondary community currency that allows for villager to villager trade in greatly shortened value chains. Especially in times of economic hardship, this currency keeps trades happening within the community, while formal national currencies (obtained from for example pensions or grants) can be used to save for larger expenses such as school fees (Ruddick, Richards and Bendell, 2015). Thus, identifying such synergies is possible, however for these to be realized, additional support for smallholder farmers is required.

Input related trade-offs (such as those between using one's own crop residues for animal fodder or using it for soil amendments, or, for consuming one's own produce or selling it) and output related trade-offs (such as having less leisure time, yet a higher operating profit) were made visible and also explored within the model output. Input related trade-offs are modelled by varying the allocation of farm products like crop residues to different destinations such as animal feed or as a soil additive to enrich soil organic matter. These input related trade-offs are then measured in terms of the output indicators which between them make the output related trade-offs visible and quantifiable. By setting realistic and achievable values for allocation of crop product destinations in participatory modelling settings, these trade-offs can be explained through the model output and can facilitate the transfer of knowledge and scaling out of innovations between researchers and advisors and farmers (cf. Figure 1.1).

FarmDESIGN also measures biodiversity indicators, and, although not examined in this study, increasing the number of crops in a farming system enhances the agro-biodiversity, which has then been linked to dietary diversity (Sibhatu and Qaim, 2018). The benefits of additional plant diversity have been shown to improve ecosystem services (Teixeira, 2020). There are also other provisional and supporting ecosystem services provided by diverse cropping systems. In Malawian farm models we also included the novel land use, 'living hedges'[1] as able to occupy up to 10% of farm area, and although these results are not yet published, the results show that including areas with these hedges, synergies emerged between protein rich fodder production, organic matter additions to the soil and nitrogen fixation by leguminous hedge crops. This improves the farming system's most important natural resource, the soil, thus increasing it's natural capital. The additional benefits from nitrogen fixation and fodder provision makes these hedges multifunctional in these farming systems. Muoni *et al*. (2019) showed that farmers in Kenya and Democratic Republic of Congo valued the short-term profit and nutrition related benefits of legume diversification the most. This potentially indicates why such hedges and other

1. Hedges comprising thorny shrubs and fodder legumes like *glyricidia*.

fodder legume diversification innovations with longer term benefits are not more widely adopted in Central Malawi. In Malawi, after the maize crop has been harvested, cattle and goats wander indiscriminately over fields and eat crop residues hampering the adoption of conservation agricultural practices of mulching (Ngwira *et al.*, 2014). For these farmers wanting to keep residues on their soil surface such fences could also prove useful in restricting livestock from eating these residues, turning trade-offs into synergies.

These trade-offs and synergies are visible as the outer surfaces of the solution spaces made up of numerous Pareto-optimal points, as illustrated in Figures 3.1, 3.2 and 4.4 in this thesis. Each solution having its own individual set of decision variables, with improved objectives. Each solution thus can be evaluated on how successfully it manages to improve incomes, close nutrition gaps and improve the provisioning of ecosystem services in these farming systems, making these trade-offs and potential synergies visible in model output. I would suggest that further research be done, using FarmDESIGN in a participatory setting, to investigate these promising nature-based solutions that manage to achieve these multiple objectives.

6.4 Assessing social diversity and generating discussions amongst like-minded farmers on similar trajectories with matching resources

Different farmers have their own preferences for particular strategies to intensify their farming system. In the sample of farmers from Central Malawi that we worked with during this study (in the period 2014 – 2020), we described clusters of farmers, using Q Methodology, who had similar strategies, and who were more inclined to favour certain trajectories of sustainable intensification. They all disagreed with purchasing staple foods like maize to ensure their food security, and preferred to grow maize to supply their own needs rather than sell it. While the low resource endowed "Seed Saving Peasants" agreed with strategies that would enhance natural capital, particularly by using their own labour to do so, "Entrepreneurial Business (wo)men" agreed with strategies to reduce their labour requirement through labour saving technologies. The "Aspirant Modern Farmers" were interested in technologies that improved their food production and also favoured technologies that enhanced the natural capital of their farms.

When further analyses were done with the same farmers, an even richer picture of the trajectories and strategies that these farmers emerged. In an article in preparation (Timler *et al*. 2021 in prep., see Appendix), a further innovative use of Q Methodology was explored. As each configuration within a solution cloud generated by FarmDESIGN has a unique set of decision variables and objectives, it was assumed that they also differed in their desirability by different farmers. Three factors were identified; "Modern Maize Farmers", who desired to be modern, plant hybrid maize, were not labour constrained, and who worked longer hours to plant seeds carefully, "Legume Integrators", who preferred traditional crop varieties over hybrid varieties, and wanted to expand the area of legume crops, and lastly, "Profit Oriented Opportunists", who focused on profit, had hired labour and had longer term goals.

The psychological capital of this sub-sample of farmers was analysed following the statements presented in a methodology by Chipfupa and Wale (2018) who called for this social construct to be included as a variable in typology construction. Upon analysis of these data, three distinct groups of farmers emerged; "Persevering Confident Farmers", "Self Reliant Optimists" and "Vulnerable Fragile Farmers" (see Appendix).

Thirteen respondents took part in all three factor analyses, and their membership in each of the three factors for each analysis is illustrated in Figure 6.1. Out of a possible 27 combinations, eight unique combinations found labeled a – h are illustrated. What is apparent is that the only "Vulnerable Fragile Farmer" (a), also desires to be modern, yet feels unequipped to have the confidence to achieve this goal, and has low confidence and resilience. Most "Aspirant Modern Farmers" are confident that using modern maize varieties and mineral fertilizer inputs (b) or integration of legumes (c) will allow them to persevere to achieve their goals. "Seed Saving Peasants" are also confident farmers with hope (d), or with resilience to system shocks through legume integration (e). Combination f is a lower resource endowed farmer with an eye for profit-making opportunities. This gives them confidence to be successful and persevere. The "Business(wo)men" with their adequate resources, are also confident that by using modern maize varieties and mineral fertilizers, they will be successful (g), while others are optimistic that, by using their business acumen, they can make use of quick opportunities with novel enterprises to succeed (h).

To complete the last steps of the INDEED cycle, Explore and Design, generic FarmDESIGN models for low and high resource endowed farmers were used in focus group discussions (FGDs) of smallholder farmers in Malawi and Tanzania (Chinosengwa, 2020; Kimisha, 2018; Kirimbo, 2017). In these FGDs, areas of promising sustainable intensification innovations were added as decision variables. Trade-off and synergies were discussed with and between farmers, desirable solutions spaces were explored, and for selected farmers, personalized farm models were created during visits to farms and farmers. Farmers were able to see the effects on indicators of their choice (economic, social and

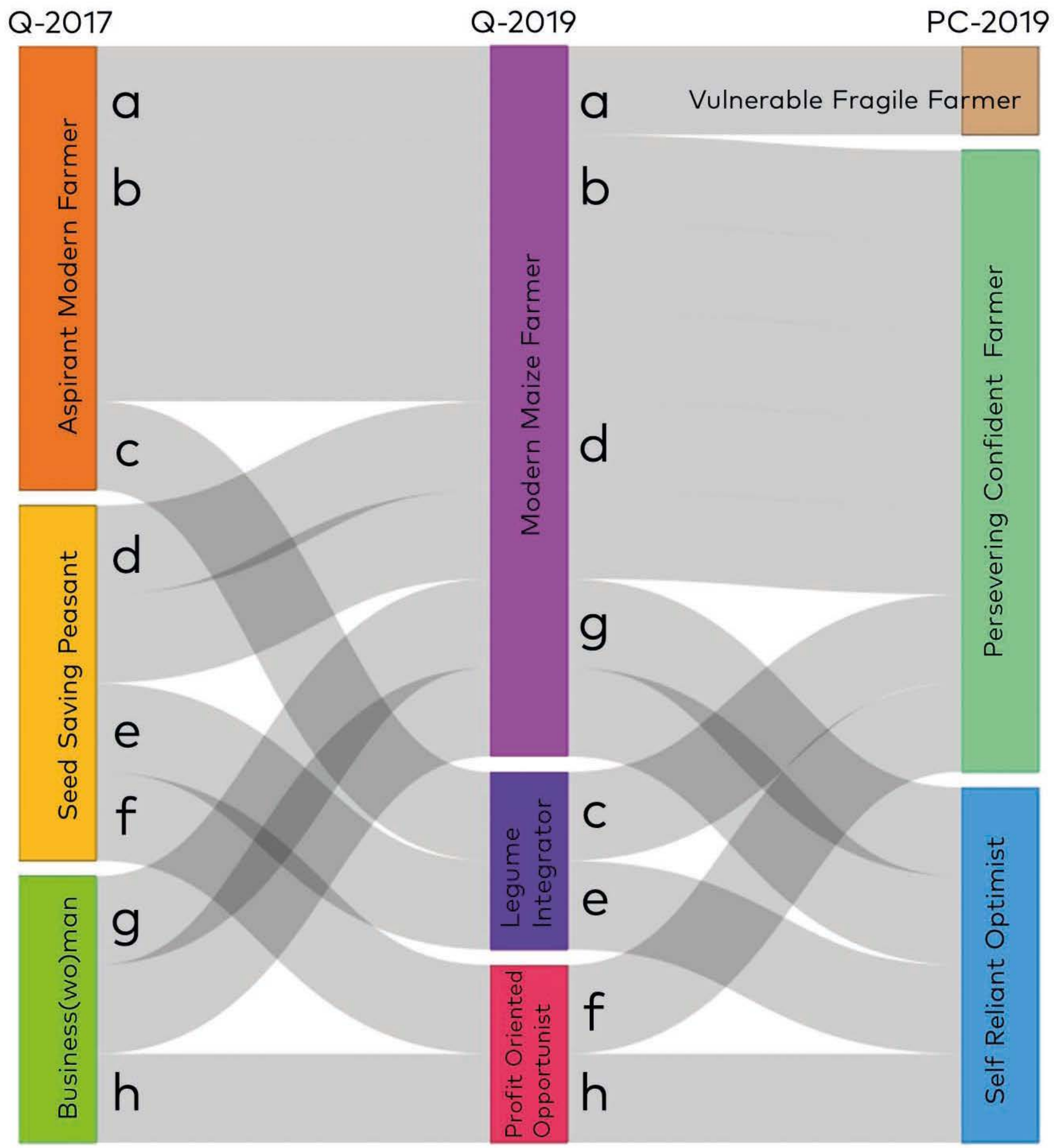

Figure 6.1 A Sankey diagram illustrating thirteen Central Malawian farmers' factor membership in the Q Methodology factors extracted in 2017 (Q-2017) and presented in chapter five (Aspirant Modern Farmers, Seed Saving Peasants and Business(wo)men) and the Q methodology and psychological capital results of 2019 (Q-2019 and PC-2019, respectively) presented in the Appendix. The letters a – h represent unique combinations.

environmental) on different crop combinations of their currently grown crops, or novel crops in FarmDESIGN. In these studies, farmers enthusiastically participated and reflected on these interactions, and thus we show how the model output aided in generating discussions with farmers in Malawi and Tanzania. We have outlined methods in which the social diversity of farmers can be assessed using Q Methodology and social constructs such as psychological capital to uncover and narrate farmer trajectories, and how this information, used with FarmDESIGN, can then aid in designing transition pathways for these diverse trajectories.

6.5 Trajectories of sustainable intensification

To visualize the trajectories of diverse farmers through a solution space, I refer to Figure 6.2. On the axes are three objectives that can be set in the model FarmDESIGN. By adding legumes, profitability can be improved, and, at the same time, protein rich legumes improve nutrition and dietary diversity. Additionally, legumes bring nitrogen into the system via biological nitrogen fixation, enabling greater yields and thus greater organic matter accumulation. Adding livestock, brings further animal products, with their ability to increase dietary diversity as well as add additional revenue sources from the sale of animal products. Livestock furthermore add nutrients through their manure, and they can function as a financial reserve, able to be sold for cash in times of need. Larger farms (red) with more area, can gain relatively larger improvements in these indicators than smaller farmer (blue), as we have shown in chapter three in Eastern Zambia.

The eight unique farmer combinations (a – h) presented in Figure 6.1 are indicated using the same letters in Figure 6.2 with the arrows representing potential development steps for these farmers through a solution space over time. Indicated with blue arrows from points e and f are two smaller "Seed Saving Peasant" farmers who focus on intensifying environmental and nutritional indicators (e) and economic indicators (f). In Figure 6.2, farmer e is shown to make use of expansion of area to have a larger farm. In post sorting interviews this farmer, a "Legume Integrator", said, *"I want to rent land to grow more legume crops, as legumes fetch high prices on the market"*. This farmer follows further hypothetical development steps with the selling and buying of livestock to aid farm cash flow for further investments in legumes, and eventually more livestock. Farmer f would be a profit-oriented farmer who would be able to wisely invest their resources to improve profit quickly. In the post sorting interviews, this farmer, a "Profit Oriented Opportunist", said, *"I love trying new things, you never know, I might benefit from the new technologies"*. This farm continues onwards with developmental steps to further increase profit, potentially also adding livestock.

Farm b in Figure 6.2, would be typical of intergenerational transfer of land. This is to a lesser degree relevant in Malawi, but very real issue for the sample of farmers we surveyed in Vihiga, Western Kenya (chapter four). The average farm size of these farms was 0.4 hectares. These farms are subdivided in the inheritance of a family head when they pass away, but are sometimes continued to be farmed as a whole by one or more descendants. However, if they are not farmed as a whole, the farm drops out of the larger farm category, but can quickly step upwards towards more optimal performance in all indicators as a smaller farm. "Vulnerable Fragile Farmers", (a), are unable to withstand shocks and through fragilization, may sell land or perhaps give up farming to find other employment (Eichenseer, 2020).

Farmers d and g are "Modern Maize Farmers" and would focus on maize-based intensification innovations with hybrid maize seeds and mineral fertilizers, while farmer c, a "Legume Integrator", is able to reap the environmental and nutritional benefits from incorporating legumes. The "Profit Oriented Opportunist" farmer h, is a successful, well resource endowed farmer that benefits by incorporating legumes to earn income and expand to include livestock.

These diverse farmers have different starting points in the solution cloud, however, our fieldwork with surveys and interviews, typology creation and use of Q Methodology showed that even farmers with similar starting points have different aspirations which guide them on their trajectory. Through the use of the output from FarmDESIGN, we can then indicate suitable regions of the solution space in which to explore redesign options for their farming systems.

6.6 Adoption of sustainable intensification opportunities

In the 1990's the concept of sustainability began to gain ground (Figure 6.3) however, as the term can quite loosely be applied, sustainability is often used as 'greenwashing' (de Freitas Netto *et al*., 2020). Within the Consultative Group for International Agricultural Research (CGIAR), the focus of attention lies on cereal-based intensification, linked to the import of external inputs such as hybrid seeds and fertilizers (Jindo, Schut and Langeveld, 2020; Ricker-Gillbert and Jayne, 2017, Holden and Lundaka, 2012). Sustainability of these systems is also given attention, however, it is framed within the context of promoting these cereal-based, plus external input intensification trajectories.

Cereal-based intensification in combination with increased external inputs led to a Green Revolution in regions such as Asia, where great improvements were made in improving production (Evenson and Gollin, 2003), yet there were also many accompanying negative effects on environmental and human health (Shiva, 1993). Similarly, in Malawi, a Green Revolution supported by the government through its infamous Fertilizer Input Subsidy Program (FISP), turned the country into a net maize exporter, however has also led to a dependence on these external input based intensification options (hybrid seeds and inorganic fertilizers) by smallholder farmers as reported by Brooks (2014). He describes a 'silent switch' to hybrid maize varieties due to a convergence of interests between funding donors, who seek to promote private sector driven solutions, the Malawian government, who seeks food security for its smallholder farmers, and multinational seed breeding companies, who are motivated financially to promote hybrid seeds. This corroborates our findings from chapter five, where the majority of farmers wanted to be "Aspirant Modern Farmers" who use these 'modern' inputs, but run the risk of their deleterious effects on their natural capital.

Pretty *et al.* in 2011 had already called for sustainable intensification in African agriculture to avoid these negative effects. They defined sustainable intensification as *'producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services'*. The imports of external inputs such as mineral fertilizers and hybrid seeds promoted as *sustainable*, indeed produce more output, however their contributions towards improving natural capital and the flow of environmental services are much less than the nature-based opportunities we outlined earlier. This leads me to the opinion that the intensification trajectories promoted by the CGIAR using hybrid seeds and use of external inputs do not meet Pretty *et al.*'s (2011) definition completely, and could questionably be called 'sustainable'.

Nutrition sensitive agricultural interventions including legume integration have greater potential to improve farm systems sustainably by also taking into account production as well as environmental and human health as we have shown in this thesis. Having explored farmers' perceptions on sustainable intensification interventions, these best-fitting interventions, presented to farmers who would be receptive to them, can hopefully be adopted. However, history shows that interventions and innovations suggested by agronomists and development specialists are infamously poorly adopted in Central Malawi (Anders, Zulu and Jambo, 2020). Much research has focused on improving adoption by exploring the process of adoption through experimentation (Hockett and Richardson, 2018), intrinsic and extrinsic motivations (Jambo *et al.*, 2019) and exploring motivation and impediment factors to adoption (Mellon-Bedi *et al.*, 2020). Mellon-Bedi *et al.* (2020) recently also used factor analysis to explore motivational and impediment factors affecting adoption in Northern Ghana. They explain three motivational factors; *personal satisfaction, eco-diversity*, and *eco-efficiency*. Interestingly in their study, personal

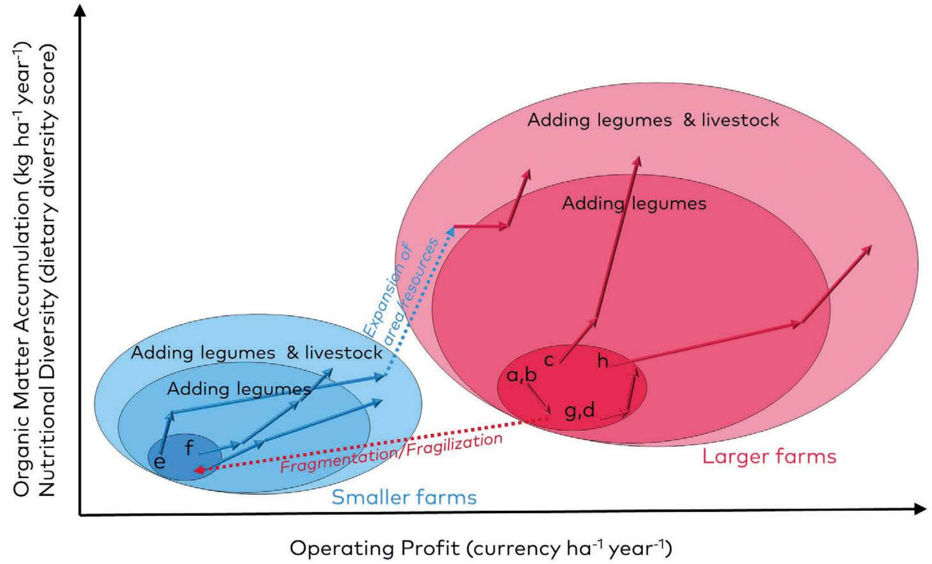

Figure 6.2 Hypothetical solution spaces of a smaller (blue) and larger (red) farms showing the larger room for improvement in operating profit and organic matter accumulation and/or nutritional diversity for larger farms. By adding legumes the solution spaces are increased, and these are increased further by adding livestock for both farms. The arrows represent the potential developmental steps over time of the farmers in Figure 6.1 (a - h). Expansion of farm area, or access to new resources can create a transition from a smaller to larger farm (e), while fragmentation of land (e.g. generational transfer) or fragilization of vulnerable famers that sell land, split larger farms into smaller farms (a or b).

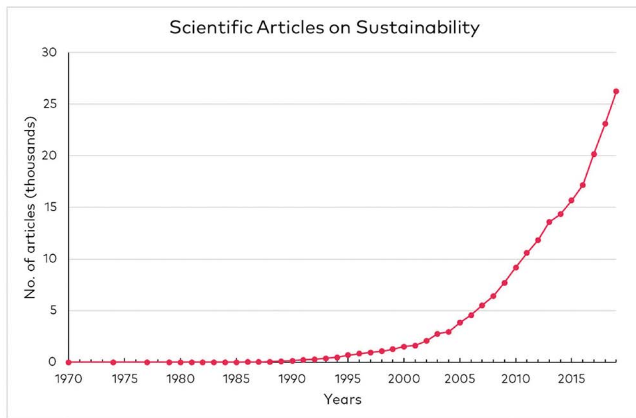

Figure 6.3 Search results on number of scientific articles using the term 'sustainability' from 1970 to 2020 (source: www.scopus.com).

in Northern Ghana. They explain three motivational factors; *personal satisfaction, eco-diversity*, and *eco-efficiency*. Interestingly in their study, personal satisfaction was linked with farmers who would be adverse to adopting modern maize varieties and who focus on self-reliance like farmer e in Figure 6.1. While *eco-efficiency* was linked to farmers with an interest in adoption of improved maize varieties, potentially similar to the "Modern Maize Farmer". *Eco-diversity* was linked with farmers wanting to improve the diversity of their crops to improve nutrition, which is quite similar to the "Legume Integrator". Hampering adoption, Mellon Bedi *et al*. (2020) show three impediment factors: *uncertainty, absence of social support*, and *resource constraints*.
Analysing the perceptions of farmers to match these with appropriate sustainable intensification options will enhance sustained adoption of these promising innovations.

6.7 A look to the future

Future research directions in which the kinds of farming systems analysis we have performed during this study can move, is through integration of satellite technology and monitoring of these smallholder systems providing data flows to, and from, the farmer. When these systems are coupled with extension services in the region of these farmers, a rapid relaying of extension advice through this three-way link between farmer, researcher and advisor (cf. Figure 1.1) is facilitated. A limitation of working with computer models and smallholder farmers is the complexity of their use and the difficulty of understanding or interpreting the model output. Future research could explore methods to reduce the technological barrier for smallholder farmers to engage with models. The output from FarmDESIGN, although understandable to some scientists, is even more complex to interpret when illiterate. Personal farm visits where this output is 'translated' by scientists to farmers are beneficial, but in order to scale out these benefits, communal approaches are more effective. These should focus on more visual representations of landscapes rather than numerical graphics. Holographic landscapes powered by whole-farm models like FarmDESIGN could potentially provide an interactive visual element whereby changes in land use or in management can be seen *in silico*.

6.8 Conclusions

In this thesis we have shown that the diversity of heterogenous farmer households can be described using typologies and Q Methodology. By using the whole-farm model FarmDESIGN, we can quantify differences in the trade-offs and synergies of suitable novel sustainable intensification innovations for different farmer types, and project trajectories of similar farmers through a solution space.

The key messages from this thesis are;

- Typology creation has to include local stakeholders and experts in the process of creation of hypotheses and in the validation of typologies.
- Some sustainable interventions are more suited to certain types of farmers, and the model FarmDESIGN can be used to explore these matches between farmer types and promoted sustainable interventions through participatory approaches.
- Traditional leafy green vegetables can improve farm livelihoods through improved diets and income generation from sales of fresh leaves, even when grown on only small areas of farmland.
- Q Methodology allows analysis of farmer perceptions which illustrate the diversity of these perceptions and can qualitatively aid in identifying potential trajectories of sustainable intensification.
- Assessing the diversity of households provides categories to group like-minded farmers together in a participatory focus group setting to discuss their option and challenges, as well as those for their communities, and learn from one another aided by output from FarmDESIGN.

6.9 Acknowledgements

I thank Rogier Schulte, Jeroen Groot and Pablo Tittonell for their constructive comments on an earlier version of this chapter.

Appendix

Use of Q Methodology and assessment of psychological capital to identify clusters of like-minded farmers in Central Malawi.

Carl J. Timler, Fungai A. Chinosengwa, Regis Chikowo and Jeroen C.J. Groot.

Introduction

Through the AfricaRISING project (www.africa-rising.net), a sample of farmers in Central Malawi has been repeatedly visited between 2014 and 2020. The study sites were in the Dedza and Ntcheu Extension Planning Areas (EPAs). In each EPA, two districts were chosen, Linthipe and Golomoti in Dedza, and Nsipe and Kandeu in Ntcheu. In each district, two villages were chosen, one that had been selected by the AfricaRISING project to have a Mother and Baby trial plot, and one that had no involvement with the project. A rapid characterization was done in April 2014 of 80 farmers (ten from each village) in Dedza and Ntcheu. From this data, a typology was created that resulted in well-, medium- and low resource endowed households. A detailed characterization was done in September 2014 with a sub-sample of twelve farms (three farmers from each district) to gain further detailed data of these three types that was used to build models in FarmDESIGN. In January 2015, these farmers were again visited to collect additional socio-economic data.

In June 2017, a sub-sample of 40 farmers were selected to take part in the Q Methodology study described in chapter five of this thesis. This study extracted three factors; "Aspirant Modern Farmers", "Seed Saving Peasants" and "Entrepreneurial Business(wo)men". In selecting the sub-sample, care was taken to include equal numbers of farmers from each endowment type. Average values for structural and functional features of farms in each factor, such as area cultivated, number of Tropical Livestock Units (TLU's) or farm income were highest for "Entrepreneurial Business(wo)men" and lowest for "Seed Saving Peasants", with the largest proportion of the sample, the "Aspirant Modern Farmers", having median values. However, these differences could not be significantly linked to the factors. This indicated that membership in a factor is potentially independent of resource endowment.

In November 2019, further Q sorting was done with a sample of farmers selected from those sampled in 2017. The research questions of this study were;
1) Can clusters of farmers that would chose similar configurations in the solution space of the model output be identified?
2) Can clusters of farmers with similar psychological capital be identified?
In this Appendix, the methodology and results of this study are presented.

Methodology

Farmers were selected and briefly visited. They were invited to a Focus Group Discussion (FGD) and initially completed a psychological capital survey ranking twelve statements following the methodology of Chipfupa and Wale (2018). Generic farm models were built and run in FarmDESIGN as outlined by Chinosengwa (2020). These models were used for demonstrations in the FGDs and served as templates for further bespoke models for individual farm visits. In creating the Q concourse for this study, the output from these models was also used as inspiration to create the statements which reflected the objectives and decision variables used in the modelling exploration. Some additional statements were created following informal discussions with farmers. The statements were sorted by seventeen of the Malawian farmers described in chapter five. Thirteen farmers completed both the psychological capital survey and the Q sorting exercise. The Q sorting results indicated the strength of agreement, or disagreement, with (distinguishing) statements for each factor. The configurations were then ranked in desirability for each factor, and in so doing, regions of the solution space were identified where desirable solutions could be found, for each factor.

Results

Three factors were extracted from the data from the seventeen Q sorts. These were entitled; "Modern Maize Farmers", "Legume Integrators" and "Profit Orientated Opportunists". The distinguishing and consensus statements for these three factors are presented in Table A1 with a full set of results in Table SA1.

Modern Maize Farmers: are farmers who desired to be modern, they wanted to plant hybrid maize seeds and took care to plant each seed well, even if it meant working longer, they were not labour constrained. They were focussed on their farming, and they were not seeking to derive additional income from off-farm work.

Legume Integrators: did not want to grow hybrid maize, they preferred to grow traditional crops. As with the "Modern Maize Farmers", they were also focussed on their farm work, and were not seeking to earn additional incomes from working off-farm. They wanted to expand the area of their legume crops because they saw opportunities for improvement of their household nutrition and the additional income earning potential from legume crops.

Profit Oriented Opportunists: were more profit oriented than the other two factors, they favoured hybrid maize, and did not grow traditional crops. They had longer term goals, and while not adverse to experimenting, had no desire to redesign their farms. They hired labour, and were not enthusiastic to integrate 'Doubled Up Legumes', they were also neutral towards adding more livestock.

The analysis of the psychological capital data resulted in three distinct clusters of farmers; "Persevering Confident Farmers", "Self Reliant Optimists" and "Vulnerable Fragile Farmers". Table A2 presents the full set of results from the analysis of the psychological capital assessment.

The majority of the farmers had high scores for confidence. These were confident farmers who believed they had the power to change their outcomes and so with this confidence would act to make changes. What "Persevering Confident Farmers" lacked was optimism. "Self Reliant Optimists" on the other hand, were more optimistic, and "Vulnerable Fragile Farmers", were least optimistic. They were distinguished by their disagreement with the statement, "*I do not give up easily*". "Self Reliant Optimists" were distinguished with a greater resilience and desire for autonomy by their disagreement with the statement, *"Government is responsible for the well-being of rural households"*. "Vulnerable Fragile Farmers" were distinguished by their disagreement with the statement, *"I can cope with shocks such as drought and other natural disasters"*. The statement *"I would not be farming if there was a better alternative"* distinguished all factors, with "Persevering Confident Farmers" strongly disagreeing, and "Vulnerable Fragile Farmers" in agreement.

In a solution cloud of 1 000 unique configurations generated by FarmDESIGN, using objectives to maximise Soil Organic Matter balance, Operating Profit and Leisure Time for a smallholder farmer in Central Malawi, the regions of the solution cloud in which the three factors, "Modern Maize Farmers", "Legume Integrators" and "Profit Oriented Opportunists" will find desirable solutions was examined. The decision variables used in generation of this output matched the statements (cf. Table SA1) of this Q concourse. The best 100 scoring solutions for each factor are presented in Figure A1.

The black triangle is the starting point, or current situation for the exploration, and, as the origin of the solution space, is also a potentially selectable configuration. "Modern Maize Farmers" would find desirable configurations in the region encompassed by the magenta points. "Legume Integrators" (purple points) have a clear trade-off between profit and labour within the range of desirable solutions, but would desire solutions with greater areas allocated to legume crops. "Profit Oriented Opportunists" who previously also flagged as "Entrepreneurial Business(wo)men" would desire red configurations with more profit, whereas "Profit Oriented Opportunists" who were previously flagged as "Seed Saving Peasants" would desire the red solutions with greater Organic Matter Balances. A "Modern Maize Farmer" who is less labour constrained would find solutions with greater profit and less free time more desirable than a labour constrained "Seed Saving Peasant", who would desire solutions with less labour demand.

Table A1: Distinguishing and consensus statements for each of the three factors extracted from the Malawi 2019 Q Methodology Study. The number to the left indicates the score given to that statement by a typical respondent that loads for that factor.

Modern Maize Farmers		**Legume Integrators**		**Profit Oriented Opportunists**	
4	**32.** I would plant one seed of maize per planting station even though it is labour-intensive to improve my yield	3	**16.** I am willing to grow legumes in addition to the staple crop maize to improve food self-sufficiency	2	**4.** I am willing to sacrifice a bit of profit for maximum soil fertility in my field
2	**30.** The farm is the future for my children and me	3	**18.** I am willing to rent land to increase my cropping area in order to grow DLR to maximize yield	2	**26.** I am willing to try new ideas even without any idea of the possible outcomes
0	**23.** I am willing to work more hours on my farm to attain food-self-sufficient rather than work off-farm for immediate but short-lived gains	0	**31.** Employment outside the farm is more important for the future	0	**21.** I am willing to increase the number of chicken as they do not require much labour and do not compete for crop residues with the field
		-2	**7.** I am willing to reduce the area of existing crops to add legumes to improve soil fertility and profit	-1	**5.** I am willing to incorporate crop residues in my field to improve soil fertility for long term sustainable crop production
		-4	**33.** I would invest in hybrid maize to increase yields	-1	**10.** I am willing to leave a greater share of the maize residues in the field and not remove it for other use to improve soil fertility
		-4	**35.** I would replace a traditional crop (like millet) with a new crop	-2	**15.** I am willing to add new crops to increase profitability despite having to work more hours
				-3	**11.** I would rather feed the residues to my animals than incorporate them in the field as they are a good source of protein
				-3	**6.** I would rather grow crops that have less labour requirements like maize than to adopt labour-intensive legume technologies even though they improve soil fertility and improve my profit margin
				-4	28. I would like to redesign my farm
-3	**14.** I am willing to grow crops that will increase my profit even though they do not contribute to maximum soil fertility	-2	**14.** I am willing to grow crops that will increase my profit even though they do not contribute to maximum soil fertility	2	**14.** I am willing to grow crops that will increase my profit even though they do not contribute to maximum soil fertility
-1	**17.** I am willing to intercrop maize with a legume to increase the yield on the same unit of land	3	**17.** I am willing to intercrop maize with a legume to increase the yield on the same unit of land	1	**17.** I am willing to intercrop maize with a legume to increase the yield on the same unit of land
-4	**34.** I would burn crop residues to save on time and labour	-3	**34.** I would burn crop residues to save on time and labour	0	**34.** I would burn crop residues to save on time and labour

Table A2: Factor scores indicating the rankings for each statement within each of the three psychological capital factors; f1: “Persevering Confident Farmers”, f2: “Self Reliant Optimists” and f3: “Vulnerable Fragile Farmers”.

Psychological Capital Statements	**Factor scores**		
	f1	**f2**	**f3**
Confidence			
1. I am confident in farming as a way of life	2	2	2
2. I am confident in myself as a farmer	2	2	1
3. I have the power to affect the outcome of my farming	2	2	1
Optimism			
4. I am optimistic about the future of agriculture	0	2	1
5. I do not give up easily	2	2	-1
6. I am willing to take more risks	1	2	1
Hope			
7. I have hope that the quality of work will improve	2	0	1
8. I am willing to forgo a profit opportunity in the short run in order to benefit from potential profits in the long run	-1	-1	2
9. I am willing to try new ideas even without full knowledge about the possible outcomes	1	1	2
Resilience			
10. I can cope with shocks such as drought and other natural disasters	-1	0	-2
11. I would not be farming if there was a better alternative	-2	-1	1
12. Government is responsible for the well-being	0	-2	1
Average reliability coefficient	0.8	0.8	0.8
Number of loading Q-sorts	11	5	2
Eigen values	9.1	4.8	2.8
Percentage explained variance	46	24	14
Standard error of factor scores	0.15	0.22	0.33

Figure A1 A solution space of 1 000 configurations generated for a Malawian smallholder farm. The three axes represent the three objectives used (to maximise) in the exploration. Superimposed are three subsets of 100 coloured solutions that represent the top scoring solutions for each factor. The three factors are Modern Maize Farmers (magenta), Legume Integrators (purple) and Profit Oriented Opportunists (red). The black triangle represents the starting point of the exploration.

Additional Data

Table SA1 Factor scores for all statements in the Malawi 2019 Q Methodology Study. Factor one is "Modern Maize Farmers", factor two is "Legume Integrators" and factor three is "Profit Oriented Opportunists". On the right side, distinguishing and consensus statements indicating statements that would significantly distinguish a factor from the others or show agreement between all factors (see also Figure SA1).

ID	Factor Scores			Statements	Distinguishing and Consensus Statements
	f1	f2	f3		
1	1	0	2	I am willing to work more hours on my farm to increase my profit	
2	1	3	3	I am willing to work more to incorporate crop residues to improve soil fertility to increase my profit	
3	-2	-1	1	I am willing to sacrifice a little profit to get more time to work off-farm for immediate cash	
4	-2	-3	2	I am willing to sacrifice a bit of profit for maximum soil fertility in my field	Distinguishes f3 only
5	2	1	-1	I am willing to incorporate crop residues in my field to improve soil fertility for long term sustainable crop production	Distinguishes f3 only
6	0	0	-3	I would rather grow crops that have less labor requirements like maize than to adopt labor-intensive legume technologies even though they improve soil fertility and improve my profit margin.	Distinguishes f3 only
7	0	-2	0	I am willing to reduce the area of existing crops to add legumes to improve soil fertility and profit	Distinguishes f2 only
8	1	1	1	I am willing to reduce areas of existing crops to increase the areas of those crops that will increase my profit	Consensus
9	-2	-2	-2	I am willing to increase the area of maize69 despite the fertilizer costs involved to increase my profit	Consensus
10	3	2	-1	I am willing to leave a greater share of the maize residues in the field and not remove it for other use to improve soil fertility	Distinguishes f3 only
11	-1	-1	-3	I would rather feed the residues to my animals than incorporate them in the field as they are a good source of protein	Distinguishes f3 only
12	-2	0	-2	I am willing to grow a doubled-up legume of pigeon pea despite it being labor-intensive	
13	-1	0	0	I am willing to grow maize-pp intercrop to improve soil fertility from the nitrogen fixation by pp and the enhanced maize residue yield despite the extra labor for pigeon pea.	Consensus
14	-3	-2	2	I am willing to grow crops that will increase my profit even though they do not contribute to maximum soil fertility	Distinguishes all
15	-1	1	-2	I am willing to add new crops to increase profitability despite having to work more hours	Distinguishes f3 only
16	0	3	-1	I am willing to grow legumes in addition to the staple crop maize to improve food self-sufficiency	Distinguishes f2 only
17	-1	3	1	I am willing to intercrop maize with a legume to increase the yield on the same unit of land	Distinguishes all
18	0	3	0	I am willing to rent land to increase my cropping area in order to grow DLR to maximize yield	Distinguishes f2 only
19	-1	0	-1	I am willing to grow a doubled-up legume of pigeon pea despite it being labor-intensive	Consensus
20	3	1	0	I am willing to increase the number of cows to boost my income and soil organic matter	

ID	Factor Scores f1	f2	f3	Statements	Distinguishing and Consensus Statements
21	3	2	0	I am willing to increase the number of chicken as they do not require much labor and do not compete for crop residues with the field	Distinguishes f3 only
22	0	2	1	I am willing to invest in hired labor to get free time for myself	
23	0	2	2	I am willing to work more hours on my farm to attain food-self-sufficient rather than work off-farm for immediate but short-lived gains	Distinguishes f1 only
24	1	-1	0	I am willing to apply fertilizer in maize despite the costs involved in order to realize a profit from the higher yields attained	
25	-4	-1	-2	I prefer to work less on the farm and more in an off-farm job	
26	-3	-3	2	I am willing to try new ideas even without any idea of the possible outcomes	Distinguishes f3 only
27	1	0	-1	Lack of knowledge prevents me from making informed decisions on-farm management	Consensus
28	0	0	-4	I would like to redesign my farm	Distinguishes f3 only
29	0	-1	0	I like to experiment and try new practices on my farm	Consensus
30	2	4	4	The farm is the future for my children and me	Distinguishes f1 only
31	-3	0	-4	Employment outside the farm is more important for the future	Distinguishes f2 only
32	4	-2	-3	I would plant one seed of maize per planting station even though it is labor-intensive to improve my yield	Distinguishes f1 only
33	4	-4	4	I would invest in hybrid maize to increase yields	Distinguishes f2 only
34	-4	-3	0	I would burn crop residues to save on time and labor	Distinguishes all
35	2	-4	3	I would replace a traditional crop (like millet) with a new crop	Distinguishes f2 only
36	2	1	1	I would sell extra produce in order to get money to sustain my family	Consensus

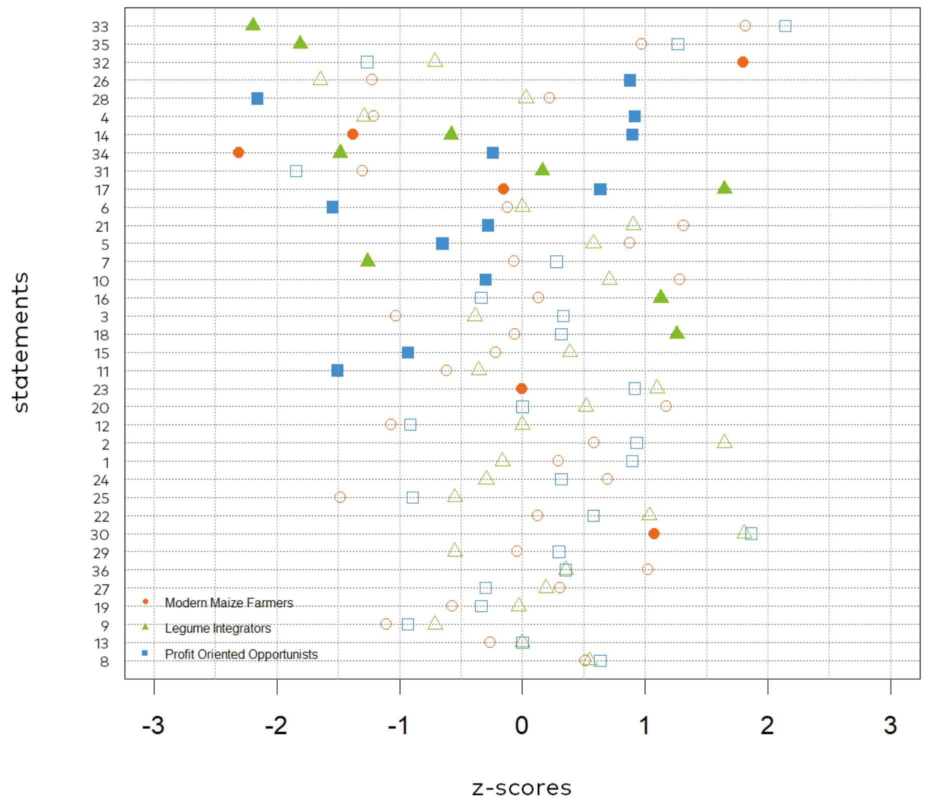

Figure SA1 z-Scores for all statements for three factors in the Malawi 2019 Q Methodology Study. For each statement; filled points are significantly different, unfilled points are not significantly different, only one filled point indicates a distinguishing statement and three filled points indicate statements which distinguish all factors (See also Table SA1).

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Summary

In the rural areas of Eastern and Southern Africa and Southern Asia, agriculture is the main activity of the inhabitants, and the vast majority of these are highly heterogenous smallholder farmers. Smallholder farming systems in themselves, are very complex and are nested within environments that are becoming increasingly more strained spatially, socially, financially and environmentally. These same systems are also responsible for producing 80% of the world's food, and thus unravelling this complexity and understanding their constraints, is key to improving nutrition and livelihoods for the burgeoning populations in these areas.

In the introduction, I present these challenges, opportunities for sustainable intensification of these farming systems and the research questions and methodologies we used to answer these. In the second chapter I showed how data sets from household surveys can be used to create statistical typologies to make sense of the heterogeneity of diverse smallholders farmers in Eastern Zambia. I demonstrated, using five separate typologies, how important the formation of a hypothesis using a panel of experts is, and how the resulting types can differ when the typology objective differs. I also proposed a methodological framework for integrating participatory and statistical methods for hypo-thesis-based typology construction in the future.

Farm models of the different types of farmers, each with their own structural and functional farm features in common can be built in the bio-economic, whole-farm model, FarmDESIGN. In Chapter three, interventions designed to integrate legumes into maize based farming systems were tested using FarmDESIGN for the different types of farmers identified through the creation of the typologies in chapter two. I explored the differing suitability of these diverse interventions for a range of farm types in Eastern Zambia. Five farm types were described as; L-LEGU, low resource endowed farmers that grow legumes and who spent most labour on land preparation, L-WEED, low resource endowed farmers that grow few legumes and spend most labour on weeding, M-LEGU, medium resource endowed farmers that grow legumes and have a high relative income from animals, MH-OFI, medium to high resource endowed farmers that have a high off-farm income, and H-LVST, high resource endowed farmers that have high crop and animal incomes. Sole legume crops like soybeans were found beneficial (i.e. higher profit, organic matter added to the soil and lower labour requirement) to L-LEGU, MH-OFI and H-LVST types, whereas L-WEED and M-LEGU types benefitted more from sole cowpea. For types L-WEED, M-LEGU and MH-OFI, including maize after the legume crop was found to be beneficial. Only the MH-OFI type was shown to have some benefit from an intercrop of maize and cowpea.

In modelling smallholder households further in chapter four, I demonstrated the ability of FarmDESIGN to make trade-offs and synergies visible, between the multiple competing objectives of farmers in Kenya and Vietnam. I created four models (two in Vihiga, Western Kenya and two in Mai Son province in North-western Vietnam) along a gradient of market orientation. The Vietnamese farms being more, and the Kenyan farms being less market oriented. I also included data on household food consumption and nutritional requirements of the farmer households. I tested intervention crops of traditional, leafy green vegetables and their ability to close nutritional gaps and concurrently improve farmers' incomes and leisure time in these farm models. For one Kenyan model, synergies were found between improving production of vitamin A and improving household budgets, however for all models trade-offs were present between labour required for intensification and profitability. The modelled results also show that by including even small areas of these vegetables, household nutritional status can be improved.

In the fifth chapter I assessed the diversity of opinions and strategies that a sample of farmers in Central Malawi have towards sustainable intensification opportunities. I hypothesized that we would find four managerial intensification pathways (MIP) these farmers might follow. To assess these opinions and strategies, I made use of Q Methodology to allow farmers to rank a concourse of statements related to these trajectories, to find clusters of farmers who rank the statements similarly. I described three distinct strategies that emerged from the factor analysis as; "Aspirant Modern Farmers", "Seed Saving Peasants" and "Entrepreneurial Business(wo)men". The largest group of farmers would aspire to become modern farmers, while the two smaller groups of peasants and business (wo)men, rely on their own labour, or desire mechanization and greater market connectiveness respectively, to intensify their production. These strategies were subsequently linked to the four hypothesized MIP's using the strength of their agreement or disagreement with statements from the Q-concourse. These three strategies did not significantly correlate with structural farm features, which might indicate that these various perspectives are independent of the level of resource endowment of farmers. I conclude from this chapter that semi-quantitative assessment of farmer aspirations and strategies could provide complementary information to structural farm typologies to support the pathways of sequential innovation decisions of farmers towards sustainably intensified farms.

In chapter six, the general discussion, I synthesize the findings from this thesis. The combination of methodologies presented in this thesis allow the researcher to identify potential trajectories of sustainable intensification. I present eight unique trajectories which are also visualized in a hypothetical solution space generated by FarmDESIGN. I describe these trajectories in the context of legume and livestock integration in the maize-based systems described in this study. To ensure the sustained adoption of these promising sustainable intensification innovation, it is imperative to analyse the perceptions of farmers, and to match these with appropriate innovations. I make suggestions for further research into participatory modelling and emphasize that attention needs to be paid towards discovering novel methods whereby the output from whole-farm models can be presented in a manner that is more understandable for farmers.

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Completing a PhD is a fine achievement for oneself, and is the capstone of one's academic career, however it is not achieved alone, there are many individuals who have contributed in diverse ways to this accomplishment. In these acknowledgements I would like to highlight these individuals and thank them for the roles they have played in this process.

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About the Author

At 10h30 in the morning of the 18th of November 1974, in the Mariannhill Monastery's Infirmary on the outskirts of Pinetown, South Africa, Carl Joachim Timler entered this world. His mother, Rosemarie Frederieke Tiedt, was a 4th generation German immigrant to South Africa. She was a school teacher at New Germany Primary School. His father, Dietmar, Hans-Jochem Wolfgang Timler was a new German immigrant, having emigrated to South Africa in 1964. He worked in the fashion industry as a menswear buyer.

Carl grew up in Pinetown suburbs, first attending a Montessori Kindergarden, and thereafter, in 1980, a local primary school. He excelled academically and in 1988, secured an entrance to Westville Boys' High School. Carl was not particularly sporty at school, but was active outdoors as a scout at 2nd Westville Scout Troop. Here he developed a love for nature, and for camping and hiking. At school he chose Biology, Physics and Accounting as major subjects in that order of interest. In 1993, with a growing ambition to become a nature conservationist or game ranger, he gained entrance to study for a Bachelor of Science in Agriculture at the University of Natal, Pietermaritzburg (now University of KwaZulu Natal).

Moving away from home, and with a newly acquired driver's license, Carl began a process of self-discovery, going places previously unvisited in his youth and making friends with divergent groups of students during the tumultuous years of the 1990's. His viewpoints becoming gradually more liberal and activist as he continued his studies. He chose 'Agricultural Production – Livestock' as a major, but became increasingly disillusioned at the conventional agronomic and animal husbandry techniques practiced by commercial farmers. His first real experience with farming systems analysis, was in his Honours year group project in 1998, a farm plan of the 7 400 ha farm, 'Craigie Burn Estates', in Greytown, South Africa.

After graduating, Carl moved to the rural area of Ixopo, working as an Office Manager for the largest seeding nursery in Southern Africa at the time, Sutherlands Seedlings. The life in the country suited him, however racial tensions over land rights in the Ixopo district made life dangerous, and after two farmers were murdered on neighbouring farms, Carl moved back to the Pietermaritzburg area, lived in Hilton, and worked as an Extension Officer with the Department of Agriculture and Environmental Affairs in Howick in 2000.

Carl quickly discovered that working with previously disadvantaged, smallholder farmers was far more interesting, more urgently needed, and thus more fulfilling than providing his free services to large scale commercial farmers. It was with these smallholder farmers that he felt his whiteness and university degree would be most effectively used to right the actions from the apartheid government, that had placed these farmers in the poverty traps they lived in, spatially, but also through policy.

Carl was familiar with permacultural principals, having spent time with organic farmers in his working area, and he wished to start an indigenous plant nursery and landscaping company, looking for land to build this on. Without a practical farming background or landscaping skills, he felt that he should broaden these practical skills by travelling abroad to the Netherlands, where this industry was exemplary.

In 2002 Carl arrived in the Netherlands, and worked in diverse nurseries and landscaping companies via *uitzendburos*. He travelled extensively in the first years he was abroad, visiting many European cities on weekend trips. After his mother passed away shortly before his 30th birthday in 2004, Carl became severely depressed and desired to return to his home country, making plans to save enough money to buy a piece of land in South Africa. His depression only lifted in 2006, when he met his future wife, Lonneke Holla, who was living in Wageningen.

In 2006 he also began a lucrative career as a telephone salesman. This job enabled him to save money to potentially return to South Africa, however his blossoming relationship with Lonneke, eventually made settling in the Netherlands more attractive. Carl then felt that it would be wise to return to his agricultural studies.

In 2009 he enrolled in the Master of Organic Agriculture program at Wageningen University. He enjoyed his studies tremendously. He used the FarmDESIGN model for his MSc thesis where he performed an analysis and redesign for 'Annapurna Farm', in Auroville, near Pondicherry, Tamil Nadu in India. An internship with Pure Graze, investigating the feasibility of grazing pigs, lead to further work with this company in 2012, running an on-farm trial near Haaksbergen after his graduation. On the 6th of November 2012, Lonneke bore Carl a son, Misha.

In 2013 Carl accepted a contract with the Farming Systems Ecology group to work with smallholder farmers in Eastern and Southern Africa through the Africa RISING project. Carl found this work extremely satisfying and this eventually lead to the development of this PhD study. on the 6th of January 2016, Carl, Lonneke and Misha welcomed Aafke Rose to their family.

Since the end of Carl's PhD contract, he continues to work in the Farming Systems Ecology group as a lecturer, and in their GIZ TAPESTRIES project in Ethiopia as researcher.

List of Publications

Peer Reviewed Journal Articles

Alvarez, S., **Timler, C. J.**, Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., Andersson, J. A., & Groot, J. C. J. (2018). Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. *PLoS ONE*, 13(5), [e0194757]. https://doi.org/10.1371/journal.pone.0194757

Estrada-Carmona, N., Raneri, J. E., Alvarez, S., **Timler, C.**, Chatterjee, S. A., Ditzler, L., Kennedy, G., Remans, R., Brouwer, I., Borgonjen van-den Berg, K., Talsma, E. F., & Groot, J. C. J. (2020). A model-based exploration of farm-household livelihood and nutrition indicators to guide nutrition-sensitive agriculture interventions. *Food Security*, 12(1), 59-81. https://doi.org/10.1007/s12571-019-00985-0

Timler, C., Alvarez, S., DeClerck, F., Remans, R., Raneri, J., Estrada Carmona, N., Mashingaidze, N., Abe Chatterjee, S., Chiang, T. W., Termote, C., Yang, R. Y., Descheemaeker, K., Brouwer, I. D., Kennedy, G., Tittonell, P. A., & Groot, J. C. J. (2020). Exploring solution spaces for nutrition-sensitive agriculture in Kenya and Vietnam. *Agricultural Systems*, 180, [102774]. https://doi.org/10.1016/j.agsy.2019.102774

Ditzler, L., Komarek, A. M., Chiang, T. W., Alvarez, S., Chatterjee, S. A., **Timler, C.**, Raneri, J. E., Carmona, N. E., Kennedy, G., & Groot, J. C. J. (2019). A model to examine farm household trade-offs and synergies with an application to smallholders in Vietnam. *Agricultural Systems*, 173, 49-63. https://doi.org/10.1016/j.agsy.2019.02.008

Peer Reviewed Book Chapters

Groot, J. C. J., Kennedy, G., Remans, R., Estrada-Carmona, N., Raneri, J., DeClerck, F., Alvarez, S., Mashingaidze, N., **Timler, C.**, Stadler, M., del Río Mena, T., Horlings, L., Brouwer, I., Cole, S. M., & Descheemaeker, K. (2017). Integrated systems research in nutrition-sensitive landscapes: A theoretical methodological framework. In I. Oborn, B. Vanlauwe, M. Phillips, R. Thomas, K. Atta-Krah, & W. Brooijmans (Eds.), *Sustainable Intensification in Smallholder Agriculture: An Integrated Systems Research Approach* (pp. 259-274). Routledge / Earthscan. https://doi.org/10.4324%2F9781315618791-18

Timler, C. J., Michalscheck, M., Alvarez, S., Descheemaeker, K. K. E., & Groot, J. C. J. (2017). Exploring options for sustainable intensification through legume integration in different farm types in Eastern Zambia. In I. Obörn, B. Vanlauwe, M. Philips, R. Thomas, W. Brooijmans, & K. Atta-Krah (Eds.), *Sustainable Intensification in Smallholder Agriculture: An integrated systems research approach* (pp. 196-209). Routledge / Earthscan. https://doi.org/10.4324/9781315618791-13

Project Reports

Timler, C. J., Michalscheck, M., Klapwijk, C. J., Mashingaidze, N., Ollenburger, M., Falconnier, G., Kuivanen, K., Descheemaeker, K. K. E., & Groot, J. C. J. (2014). *Characterization of farming systems in Africa RISING intervention sites in Malawi, Tanzania, Ghana and Mali.* (Africa RISING). Wageningen University.

Michalscheck, M., **Timler, C. J.**, Descheemaeker, K. K. E., & Groot, J. C. J. (2014). *Characterization of farming systems in Africa RISING SIMLEZA intervention sites in Zambia*. International Institute of Tropical Agriculture. https://africa-rising.wikispaces.com/file/view/Zambia-AR-SIMLEZA-Report+(merged+document).pdf

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Groot, J. C. J., Alvarez, S., **Timler, C. J.**, Paas, W. H., Descheemaeker, K. K. E., & Brouwer, I. D. (2015). *Systems analysis in nutrition sensitive landscapes*. 11-12. Abstract from International Conference on Integrated Systems Research, Ibadan, Nigeria. http://humidtropics.cgiar.org/wp-content/uploads/downloads/2015/02/Conference-Book-of-Abstracts-Small.pdf#page=11

Groot, J. C. J., Klapwijk, C. J., **Timler, C. J.**, Bekunda, M., van Mourik, T., Descheemaeker, K. K. E., Tittonell, P. A., Giller, K. E., Snapp, S., & Vanlauwe, B. (2013). Rising to the challenge of sustainable intensification of agricultural production in Africa – farming systems design to support action research for development. In F. Chen, & W. Gao (Eds.), *Proceedings of the 4th International Symposium for Farming System Design, 19-22 August 2013, Lanzhou, China* (pp. 167-168).

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Paul, B. K., Birnholz, C., Groot, J. C. J., Herrero, M., Notenbaert, A., **Timler, C.** J., Klapwijk, C. J., & Tittonell, P. A. (2015). *Potential multi-dimensional impacts and tradeoffs of improved livestock feeding scenarios in Babati, Tanzania.* Abstract from Climate Smart Agriculture Conference, 16-18 March 2015, Montpellier, France, Montpellier, France. https://edepot.wur.nl/375408

Timler, C. J., Michalscheck, M., Klapwijk, C. J., Mashingaidze, N., Ollenburger, M. H., Falconnier, G. N., Kuivanen, K., Descheemaeker, K. K. E., & Groot, J. C. J. (2015). *Exploring options for sustainable intensification in different farming system types of four Africa RISING countries.* 23-24. Abstract from International Conference on Integrated Systems Research, Ibadan, Nigeria. https://edepot.wur.nl/375291

Working Documents

Paul, B. K., Birnholz, C., **Timler, C. J.**, Michalscheck, M., Koge, J., Groot, J. C. J., & Sommer, R. (2015). *Assessing and improving organic matter, nutrient dynamics and profitability of smallholder farms in Ethiopia and Kenya: Proof of concept of using the whole farm model FarmDESIGN for trade-off analysis and prioritization of GIZ development interventions.* (CIAT working document; No. 408). CIAT International Center for Tropical Agriculture. https://edepot.wur.nl/371653

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)
- Research gaps in smallholder farming systems analysis in developing countries, SIAS discussion group (2015)

Writing of project proposal (4.5 ECTS)
- Multi-scale exploration of trade-offs in small scale farming systems in Eastern andSouthern Africa (2015)

Post-graduate courses (3.9 ECTS)
- Agriculture by design; WUR (2014)
- Art of modelling; PE&RC (2015)
- COMMOD; PE&RC /WASS / SENSE (2016)
- Introduction to statistics in R; PE&RC / SENSE (2017)

Laboratory training and working visits (1 ECTS)
- Ex ante assessment gergera watershed, Tigray, Ethiopia, preparation; University College Cork (UCC), Ireland (2019)
- Ex ante assessment gergera watershed, Tigray, Ethiopia, creation data collection plan and survey tool + field visit; Mekelle University, ICRAF, UCC (2020)

Invited review of (unpublished) journal manuscript (1 ECTS)
- Ciencia Rural: typology of smallholder Hass avocado farmers in Colombia (2019, 2020)

Competence strengthening / skills courses (1.2 ECTS)
- Last stretch of PhD; PE&RC (2018)
- Writing propositions; PE&RC (2018)
- Supervising BSc & MSc students; Education Support Centre (2019)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.1 ECTS)
- PE&RC First year weekend (2015)
- PE&RC Mid-term weekend (2017)
- PE&RC Last year weekend (2018)

Discussion groups / local seminars / other scientific meetings (4.8 ECTS)
- SIAS (2014-2018)
- World without pesticides: hunger or paradise (2015)
- Tipping points in pest management (2016)
- Resilience coping with change (2017)
- Wageningen PhD symposium (2018)
- WaCASA (2019-2020)

International symposia, workshops and conferences (3.5 ECTS)
- International Conference HumidTropics; Ibadan, Nigeria (2015)
- Sustainable Development Goals Conference; Wageningen (2018)

Lecturing / supervision of practicals / tutorials (6.6 ECTS)
- Ecological design & permaculture; Wageningen, the Netherlands (2014)
- Farming systems analysis & modelling; China Agricultural University, Beijing, China (2015)
- FarmDESIGN workshop; CIMMYT science week, Gansu Agricultural University, Lanzhao, China (2015)
- FarmDESIGN workshop; CIMMYT ESAP System Analysis Tools Project, Addis Ababa, Ethiopia (2017)

Supervision of MSc students (12 ECTS)
- Engaging smallholder-farmers in model-based identification of alternative options, trade-offs and synergies for sustainable intensification in North-Tanzania
- Exploring windows of opportunities, trade-offs and synergies for improving farmers livelihoods and strengthening human and environmental health in Central Malawi
- Tomme des Pyrenees PGI – whats in a name? Q-methodology study on farmstead artisanal cheesemakers perceptions on the Tomme des Pyrenees Protected Geographic Indication (PGI)
- Identifying optimal soil conditions for successful Cyclopia subternata cultivation in the Langkloof and Kouga region, South Africa

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