UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND ENVIRONMENT

Institute for Complex Systems Simulation

Centre for Environmental Sciences

Volume 1 of 1

The Potential of Agent-based Modelling as a Tool to Unravel the Complexity of Household Food Security:

A Case Study of Rural Southern Malawi

by

Samantha Louise Dobbie

Thesis for the degree of Doctor of Philosophy

September 2016

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND ENVIRONMENT

Complex Systems Simulation

Thesis for the degree of Doctor of Philosophy

The Potential of Agent-based Modelling as a Tool to Unravel the Complexity of Household Food Security: A Case Study of Rural Southern Malawi

Samantha Louise Dobbie

Household food security is shaped by the way in which households acquire and utilise assets, within a context of vulnerability. The multiple interactions between the various factors that affect the livelihoods of households give rise to often complex and non-linear system behaviour. Conventional policies have failed to eradicate food insecurity within developing country contexts. There is a need for new approaches to direct the design and implementation of interventions that address the multi-scalar and dynamic nature of food security. One possible technique is agent-based modelling, which comprises a computerised simulation of agents located within an environment. Behaviour at the system level is an emergent property of the collective behaviour at the local level, resulting from the interactions between agents and the environment through predisposed rules. Within Malawi, the vast majority of the rural population is engaged in subsistence farming. Continued reliance upon rain-fed agriculture renders smallholders vulnerable to climatic shocks, whilst high population densities, small plot size and poor soil quality further compound food insecurity. The overarching aim of this project was to explore the potential of agent-based modelling to unravel the complexity of household food security within rural Southern Malawi. As a starting point, we used cluster analysis of household survey data to construct a typology of rural households. This drove the design of an agent-based model (ABM) that takes into account the availability, access, utilisation and stability components of food security. Techniques from exploratory modelling and analysis were then employed to explore model uncertainty and identify potential pathways to alleviate food insecurity of households within rural Southern Malawi. The ability of agent-based modelling to address the complexity of food security was then evaluated. The model was found to be highly salient. However, future work will need to enhance the credibility and legitimacy of the tool. It is only then that the true potential of ABM's in addressing the complexity of rural food security will be fulfilled.

Table of Contents

List of Tables

List of Figures

DECLARATION OF AUTHORSHIP

I Samantha Dobbie, declare that this thesis entitled 'The Potential of Agent-based Modelling as a Tool to Unravel the Complexity of Household Food Security: A Case Study of Rural Southern Malawi' and the work presented in this thesis are both my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published (see below).

Chapter two of this work was developed primarily by S. Dobbie, with direction from K. Schreckenberg and J. G. Dyke. It has been resubmitted to *Food Security* (following review) as:

Dobbie, S., Dyke, J. G., & Schreckenberg, K. (in review). Unpacking Diversity: Typology Creation and Livelihoods Analysis to Support Food Security Policy in Rural Southern Malawi. *Food Security*.

Chapter three was developed by S.Dobbie with direction from S. Balbi, K. Schreckenberg and J.G. Dyke. The majority of model code was developed by S. Dobbie with technical assistance from S. Balbi. A village dataset for rural Malawi was provided by M. Schaafsma. The chapter has been submitted to *Journal of Artificial Societies and Social Simulation* as:

Dobbie, S., Schreckenberg, K., Dyke, J., Schaafsma, M., Balbi, S. (submitted). Agent-based Modelling to Assess Community Food Security and Sustainable Livelihoods. *Journal of Artificial Societies and Social System.*

The chapter expands upon earlier work which was accepted for the 11th conference of the European Social Simulation Association. This has been published as:

Dobbie, S. & Balbi, S., (2017). Design of an Empirical Agent-Based Model to Explore Rural Household Food Security Within a Developing Country Context. In *Advances in Social Simulation 2015* (pp. 81-94). Springer, Cham.

Chapter four was developed by S. Dobbie , with direction from K. Schreckenberg, S. Balbi and J. G. Dyke. It is yet to be submitted as a journal article.

Signed:

Date: 09/06/2017

Acknowledgements

This thesis would not have been possible without the support of my supervisors, Kate Schreckenberg and James Dyke. Thanks should also be given to Stefano Balbi for his relentless enthusiasm for the project; as well as Marije Schaafsma for generously supplying data (and the occasional pep talk) when it was needed. Thank you to the ASSETS team for inspiring this project, in particular Simon Willcock; as well as friends and family for all the welcome distractions. In particular, a huge thank you to Joe Osborne for all the proof reading and delivery of excessive cups of tea that kept me writing. Finally, Doreen Pretty, this one's for you! For your love of food and the belief that no one need go hungry. We all stand on the shoulders of giants, it just so happens that mine was 5ft1 (and a bit).

This work was supported by an EPSRC Doctoral Training Centre grant (EP/G03690X/1). It was also inspired by an ESPA funded research project: Attaining Sustainable Services from Ecosystems (ASSETS), which aims to "explicitly quantify the linkages between ecosystem services that affect and are affected by food security and nutritional health for the rural poor at the forest-agricultural interface" (http://espa-assets.org/).

Abbreviations

ABM	Agent-based Model
AME	Adult Male Equivalent
ARIES	ARtificial Inteligence for Ecosystem Services
ASSETS	Attaining Sustainable Services from Ecosystems through Trade-off Scenarios
ASWAp	Agricultural Sector Wide Approach
CAADP	Comprehensive African Agricultural Development Programme
EAR	Estimated Average Requirements
EMA	Exploratory Modelling and Analysis
GNI	Global National Income
HCES	Household Consumption and Expenditure Surveys
HDDS	Household Dietary Diversity Score
HFVS	Household Food Variety Score
IHS3	The Third Integrated Household Survey (in Malawi)
LHC	Latin Hypercube Sampling
MDG	Millennium Development Goal
NACL	National Census of Agriculture and Livestock
NCA	Ngorongoro Conservation Area
NGO	Non-governmental Organisation
ODD	Overview, Design concepts and Details
PHEWS	Pastoral Household and Economic Welfare Simulator
PRA	Participatory Rural Appraisal
PWP	Public Works Programme
RMSE	Root Mean Squared Error
SCTS	Social Cash Transfer Scheme
SDG	Sustainable Development Goal
SLF	Sustainable Livelihoods Framework

Chapter 1: Introduction

1.1 Problem Statement

Early approaches to the conceptualisation of food security focused predominantly upon food availability (UN, 1974). The 1996 world summit plan of action however, defined food security as a state in which *"all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life"* (FAO, 1996). This not only highlighted the need to acknowledge the multidimensional nature of the phenomenon, but later led to the identification of the four pillars of food security, namely availability, access, utilisation and stability (FAO, 2004).

Complex social, ecological and political factors act to undermine the realisation of food security currently (Sahley *et al.*, 2005). On a global level, between 2014 and 2016 a total of 795 million, or 1 in 9 people were considered to be food insecure (FAO *et al.*, 2015). The sustainable development goals (SDG) adopted by the United Nations have set a clear target to end food insecurity by 2030. The aim of Goal 2 is to *"end hunger, achieve food security and adequate nutrition for all, and promote sustainable agriculture"* (UN, 2015b, p.18). In order to address food insecurity, three distinct policy agendas have dominated the discourse. These are based upon productivist, nutritionist and social protection strategies, respectively (De Schutter, 2014).

Improved infrastructure and market access, in addition to innovations to close the yield gap, constitute productivist strategies (Pretty *et al*., 2011; Pradhan *et al*., 2015). Nutritionist strategies tackle inadequate food intake, excessive food intake and micro-nutrient deficiencies (Pinstrup-Andersen, 2007). This may be achieved through educational campaigns to promote good feeding practices, along with the fortification of foods and improved access to clean water and sanitation (Lassi *et al*., 2013; Ruel and Alderman, 2013; Ngure *et al*., 2014). Finally, social protection strategies call for the introduction and preservation of safety nets such as conditional cash transfers and public works programmes to alleviate food insecurity (Devereux, 2016).

In order to achieve food security by 2030, there is a need to assess the impact of such productivist, nutritionist and social protection strategies upon the food security status of households over time. Studies by Fanzo and Pronyk (2011), Fan *et al.* (2015) and Scherpbier (2016) have considered how different combinations of the three strategies have addressed food insecurity within Brazil, China, Thailand and Vietnam. In each case, the combined impact of productivist, nutritionist and social protection strategies was evaluated in terms of either the prevalence of underweight children under five years of age and/ or the proportion of the population below a minimum level of dietary energy consumption (Fanzo and Pronyk, 2011; Fan *et al.,* 2015; Scherpbier, 2016). Together, these indicators provide a good indication of the availability of food and its consumption, however they fail to take into account the multidimensional nature of food security. Access and utilisation aspects of food security for example, are neglected when using these indicators.

The need to better take into account the complexity of food security has prompted calls for novel approaches that link research, policy and practice (Chaudhury *et al*., 2013). Cash *et al.* (2003) advocate the use of boundary organisations to act as intermediaries between the realms of science and policy, and enhance the salience, credibility and legitimacy of information produced. This can be achieved through the creation of boundary objects, which are described by White *et al*. (2010) as hybrid constructs that promote negotiation and exchange between scientists and policy makers. A simulation tool, modelling household decision-making could illuminate the drivers of food insecurity and exist at the boundary between science and policy.

1.1.1 The Potential of Simulation Tools

Previous attempts have been made to employ modelling techniques in evaluating strategies that promote food security amongst smallholder households. Masters *et al*. (2000) for instance, define an optimization model that interprets the relationship between household nutritional intake and labour productivity, with added consumption, resource and borrowing constraints. The model is calibrated with household survey data for Malawi and employed to investigate two broad policies: firstly, the input-market liberalisation program for tobacco and other crops, and secondly, implementation of the Starter Pack Scheme for input subsidies (Masters *et al*., 2000). Application of the model provided further evidence for the link between access to inputs and improved household income and food production (Maters *et al*., 2000). However, the food security status of households was poorly defined by the authors and appears to be synonymous with food production and purchasing power. This overlooks key components of food security such as the ability of households to utilise food.

Dorward (2003) documents the development of mathematical farm/ household models to explore responses to change in the form of maize price increases and fertiliser use. Model results highlighted the role of social protection strategies such as universal credit in promoting pro-poor growth (Dorward, 2003). Research gaps were also uncovered by the model, including the need for greater understanding of rural labour markets (Dorward, 2003). The importance of representing the behaviour of individual households and interactions between them was also described as a key lesson of the approach (Dorward, 2003).

Thangata *et al*. (2002) outline the use of a dynamic mathematical model to decipher drivers of agroforestry adoption and household decision-making. The model was applied to identify conditions leading to improved fallow within rural areas of Malawi. Similar to Masters *et al*. (2000), the link to food security was simplified by Thangata *et al*. (2002), with attention given to food production and calorie needs.

According to Mena *et al*. (2014), it is the complex social-ecological nature of smallholder dynamics, which causes agent-based modelling to be an appropriate tool for studying food security. This technique consists of a computerised simulation of agents located within an environment, which interact through predisposed rules (Farmer and Foley, 2009). Behaviour at the system level is an emergent property of the collective behaviour of individual agents at the local level (Matthews *et al*., 2007). A number of studies have employed agent-based models (ABMs) to investigate aspects of social-ecological systems, for example: models of resource management, land use change and spread of innovations (Deadman *et al*., 2004; Johnson *et al*., 2006; Schlüter *et al*., 2007).

In this thesis I focus on empirical ABMs. In these ABMs, rules that govern the behaviour of agents and the environment are centred upon empirical observation. Such models offer the potential to explore the effect of real-world policies and investigate scenarios, providing a boundary object at the interface between science and policy (Parker *et al*., 2003; Matthews *et al*., 2007). Agent-based modelling has provided a useful tool in the study of complex social-ecological systems. However, as a relatively novel approach standard methodological frameworks for the development of ABMs are yet to be agreed upon. The application of models to design policy and aid decision-making has been met with mixed success. According to Bankes (1993) issues associated with the use of models arise from confusion between two different simulation approaches, namely consolidative and exploratory modelling.

Typically, models are constructed by consolidating known facts into a single package. This is then employed as a surrogate for the actual system and used in a predictive manner to generate optimal solutions. In contexts dominated by uncertainty, however, Bankes (1993) argues that the consolidative approach can no longer be applied. Limited evidence surrounding the exact mechanisms underpinning complex problems can lead to several alternative, but equally viable models of the system of interest. Under these circumstances exploratory modelling techniques, rather than consolidative approaches should be considered (Bankes, 1993).

Exploratory modelling and analysis (EMA) provides a research methodology to systematically explore the consequences of uncertainty through a series of computational experiments (Kwakkel and Pruyt, 2013). Using computational models as scenario generators it is possible to analyse complex systems taking into account parametric, structural and methodological uncertainties (Kwakkel and Pruyt, 2013). Unlike consolidative modelling, the output of EMA does not provide a surrogate of the target system. Instead, it delivers a computational experiment inferring how the world would behave if the various estimates and assumptions were correct (Bankes, 1993). To date, EMA has been applied to the study of climate change, economic policy and transport (Lempert and Schlesinger, 2000; Kann and Weyant, 2000; Zhao and Kockelman, 2002). In these cases EMA has proven useful for the design of robust policies across multiple scenarios and enabled trade-offs amongst policies to be explored.

1.1.2 Developing an ABM of Household Food Security

The process of developing an ABM can pose a number of challenges, particularly within data scarce environments (Valbuena *et al*., 2008). Smajgl *et al*. (2011) propose 12 possible sequences for the characterisation and parameterisation of human behaviours. These are founded upon two 'fundamental steps', namely, the development of behaviour categories and scaling to the whole population of agents (Smajgl *et al*., 2011). Smagjl *et al*. (2011) argue that selection of a particular modelling sequence is dependedent upon the context. The number of agents to be constructed within the model and its overall aim, combined with the availability of empirical data will dictate the sequence of actions required to characterise and parameterise model agents (Smagjl *et al*., 2011).

In order to categorise households, Valbuena *et al*. (2008) recommend typology formation. Here distinct household types are identified based upon shared attributes and livelihood strategies (Valbuena *et al*., 2008). It is in this context that an analytical framework, such as the Sustainable Livelihoods Framework (SLF) may be of great use.

Initially defined by Chambers and Conway (1991), the SLF seeks to understand the way in which households acquire and utilise assets to form livelihood strategies, given a context of vulnerability (Fig. 1.1). Shocks, trends and seasonality comprise the vulnerability context. According to DFID (1999) examples of trends include (but are not limited to) long-term changes in population size, resource use, economic status and governance. Shocks refer to short-term events that may be economic, ecological or social (DFID, 1999), whilst seasonality reflects the cyclical nature of resource prices, production outputs, human health and/or employment opportunities (DFID, 1999). The vulnerability context has a direct impact upon a household's assets in the form of human, natural, financial, physical and social capital (Chambers and Conway, 1992). Underlying policies, institutions and processes (PIPs) also act to shape access to particular assets or poverty reducing factors (Chambers and Conway, 1992; DFID, 1999).

Livelihood strategies are defined as *"the range and combination of activities and choices that people make/undertake in order to achieve their livelihood goals (including productive activities, investment strategies, reproductive choices, etc.)"*, (DFID, 1999, p.23). In the SLF, they arise from the way in between the various factors that affect livelihoods in order to achieve livelihood outcomes (Fig. 1.1). More income, increased well-being, reduced vulnerability and improved food security are all examples of possible livelihood outcomes (DFID, 1999).

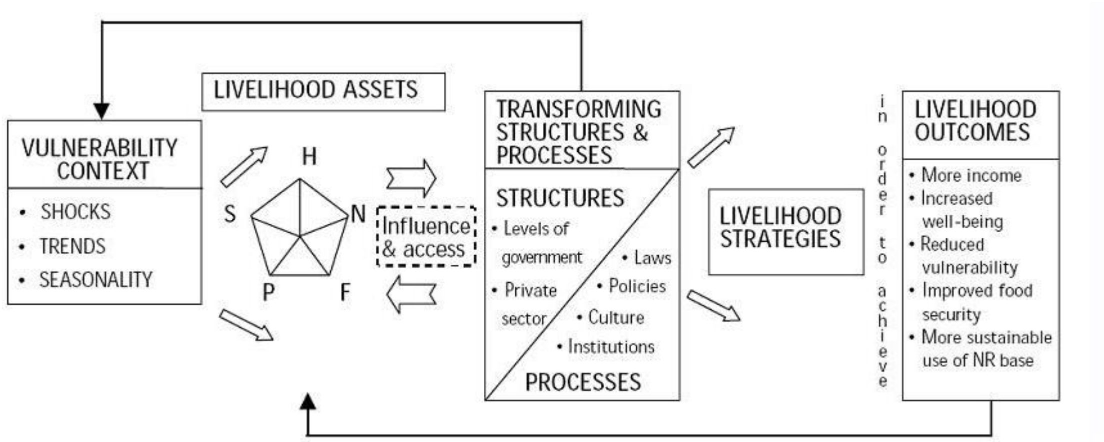

Figure 1.1: The Sustainable Livelihoods Framework. H: human capital; N: natural capital; F: financial capital; P: physical capital; S: social capital. Adapted from DFID (1999)

1.2 Research Aims and Objectives

The overarching aim of the research is to explore the potential of agent-based modelling to better understand the complexity of rural household food security. To achieve this aim I will focus on six key research questions:

1. What are the key livelihood strategies of rural households within southern Malawi?
2. How do the different livelihood strategies influence food availability, access, utilisation and stability?
3. Can agent-based modelling provide a useful tool to operationalise the sustainable livelihoods framework?
4. How can an empirical ABM be constructed and validated in data scarce environments?
5. Once built, can this simulation tool be used to identify robust pathways to zero hunger by 2030?

6. How can trade-offs and synergies between productivist, nutritionist and social protection strategies to zero hunger be harnessed?

Three objectives emerge from the research questions outlined above:

Objective 1: To identify key livelihood strategies of rural households. Cluster analysis of household survey data will be used to construct a typology of rural households within Southern Malawi. The SLF will be operationalized to explore the food security status of different household types.

Objective 2: To develop an empirical ABM of household food security. This will require the design of a simple ABM employing decision trees to represent farmer decision-making. Agents will correspond to the household types identified through the first objective. The model will be calibrated and validated using household survey data and expert knowledge.

Objective 3: To use the ABM to identify robust pathways towards zero hunger by 2030. Techniques from EMA will be used to balance trade-offs and synergies between productivist, nutritionist and social protection strategies.

Research gaps associated with each of these objectives are explored in depth within Section 1.5.8.

1.3 Overview of Methods

In order to achieve each of the objectives described above, a set of methods was developed (Fig. 1.2). In this section, I provide a brief overview of the methods and accompanying data, which are described in detail throughout the course of this thesis.

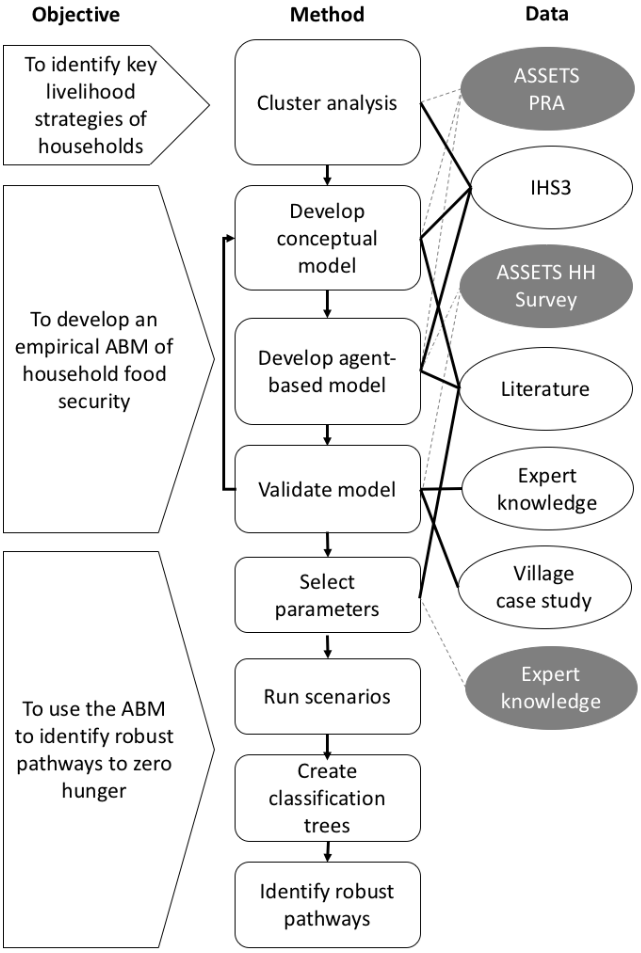

Figure 1.2: Overview of thesis objectives, corresponding methods and associated data. Intended data sets are represented by shaded ovals; actual data sets are represented by unshaded ovals. PRA: participatory rural appraisal; IHS3: third integrated household survey for Malawi.

Initial research design was guided by collaboration with Attaining Sustainable Services from Ecosystems through Trade-off Scenarios (ASSETS). ASSETS is an ESPA funded project which aims to *"explicitly quantify the linkages between ecosystem services that affect – and are affected by – food security and nutritional health for the rural poor at the forest-agricultural interface"* (http://espa-assets.org/).

The project selected case studies from Sub-Saharan Africa and Amazonia to enable comparison between sites at different stages along a deforestation gradient (ASSETS, 2011). A total of three countries were identified, including Malawi, Peru and Colombia. Many of the same external drivers are thought to affect food security, nutritional health and ecosystem services within these countries (ASSETS, 2011). However, local pressures also provide important differences between each of the case studies (ASSETS, 2011).

Food security remains a deep-seated issue throughout Sub-Saharan Africa (FAO *et al*. 2015) and so for this thesis I chose to focus upon Malawi. ASSETS followed a transect within Malawi, running from Lake Chilwa up the mountain to the Zomba Forest Reserve and down the other side (Schreckenberg, 2016, pers. comm.). The project aimed to work in six villages with different levels of (physical) access to the lake and forest ecosystems, as well as different access to markets (Schreckenberg, 2016, pers. comm.). To achieve the aims of the project, ASSETS planned to collect a wide range of data at different scales (Fig. 1.3).

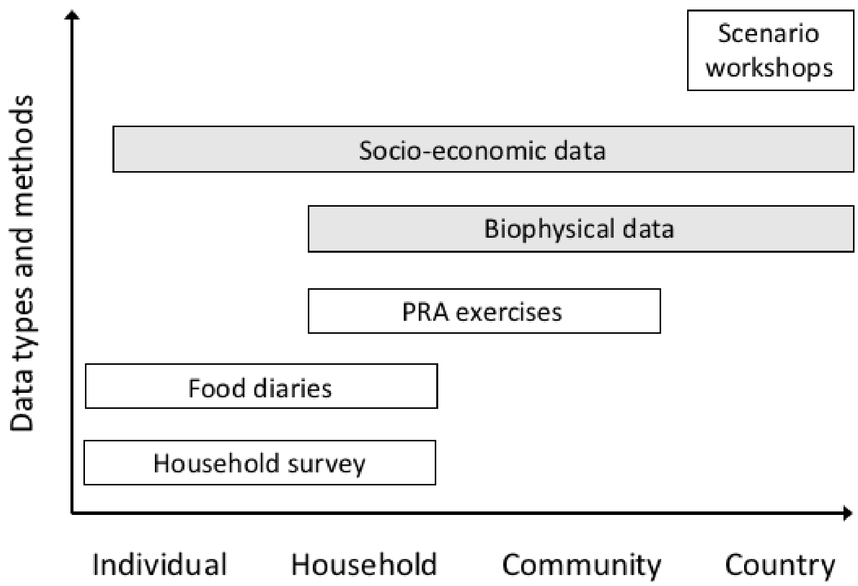

Figure 1.3: Types of data and methods collected at different scales by ASSETS. Shaded boxes: secondary data; unshaded boxes: primary data; PRA: participatory rural appraisal. Adapted from Schreckenberg *et al.* (2016).

For this thesis, I intended to use results from participatory rural appraisal (PRA) wellbeing ranking exercises to define household types (Fig. 1.2). Fieldwork conducted within Malawi during the summer of 2013 was used to develop a proof of concept (Dobbie *et al*., 2015). Analysis of additional PRA exercises including: seasonal calendars, land use discussions and coping strategies focus groups (see Schreckenberg *et al*., 2016) were also to be taken into account. It was anticipated that results from these exercises would firstly, inform the conceptual model and secondly, provide qualitative data for the development of model behavioural rules. Quantitative data from the ASSETS household survey was also to be used to aid model development and validation. It was expected that the ASSETS project would provide six case study villages with which to parameterise and empirically validate the model. Having constructed the ABM, it was also thought that continued involvement of ASSETS partners would provide expert knowledge to help identify policy areas of interest and guide subsequent EMA under objective 3 of this thesis.

Model outputs from a number of scenarios would be used to grow classification trees and identify robust pathways to zero hunger (See Fig. 1.2).

Unfortunately delays to the ASSETS data collection process meant that a number of alternative data sets had to be sought for this thesis. Instead of relying upon the results from incomplete PRA exercises, the identification of livelihood strategies was based upon cluster analysis of the third integrated household survey dataset for Malawi (IHS3) (NSO, 2012). This survey, conducted by the National Statistical Office of Malawi between 2010 to 2011, collates detailed information on the welfare and socio-economic status of Malawian households (NSO, 2012). Development of the ABM was based primarily upon the IHS3 and relevant literature (See chapter 3). Model validation did elicit expert knowledge from ASSETS and related project partners (see chapter 3), however the ASSETS household survey data was unavailable and as a result could not provide village case studies. Instead, data for a single village from a separate research project was used to parameterise and validate the model empirically (see chapter 3). Finally, when using the model to identify pathways to zero hunger, there was no opportunity to draw on expert knowledge from the project to identify parameters of interest. As an alternative, selection of suitable parameters was based upon relevant literature (see chapter 4).

1.4 Thesis Structure

This thesis is made up of five chapters (Fig. 1.4). The remainder of chapter one provides an outline of the research study and a review of the literature. The review considers how food security has been conceptualised in the past and why food security represents a complex social, ecological problem. The potential of agent-based modelling to address three key issues arising from the complex nature of rural food security is then evaluated. Issues considered include: firstly, the need for non-linear models, secondly the need for qualitative analysis and thirdly the importance of using a multiplicity of perspectives. The review moves on to introduce the case study area of rural southern Malawi, before identifying research gaps to be tackled throughout the course of the thesis.

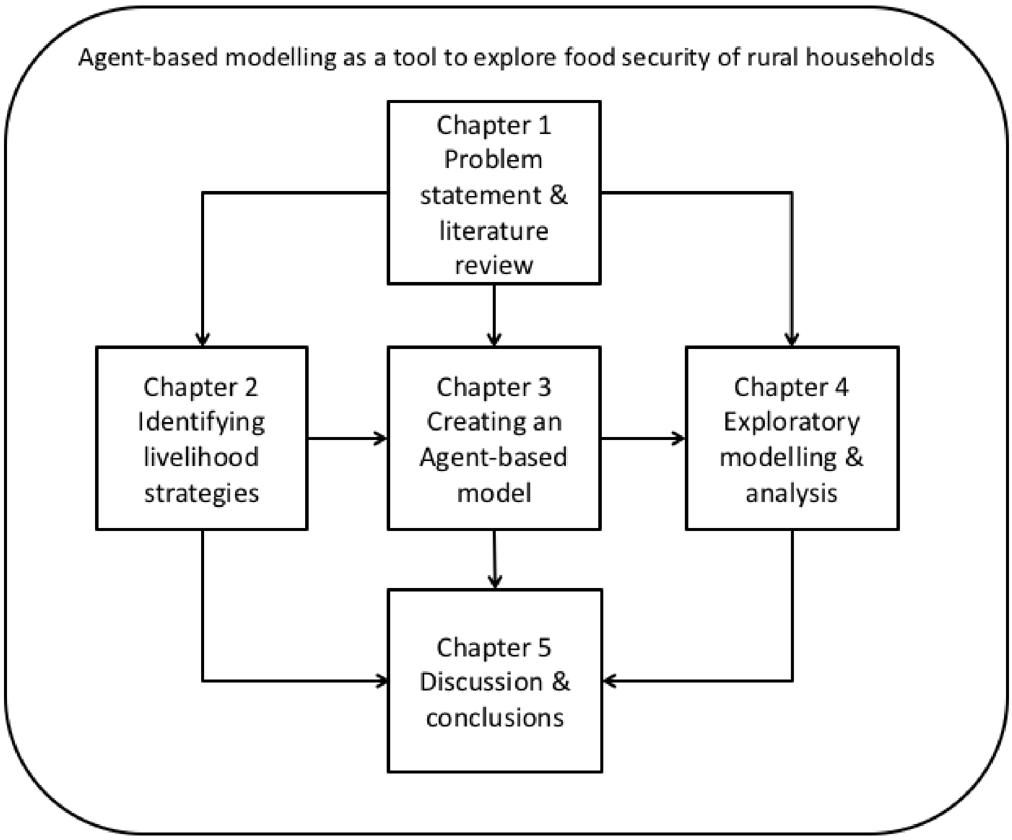

Figure 1.4: Thesis structure.

Chapter two describes a methodology for the creation of household typologies. The approach is applied to the case study area of rural southern Malawi. In addition, the chapter documents the application of the SLF in a bid to better understand the way in which households interact with one another and acquire and utilize assets to form livelihood strategies, given a context of vulnerability and the underlying impact of policies, institutions and processes. A recent household consumption and expenditure survey for Malawi is used to compare the caloric consumption of individuals, as well as the micronutrient content of diets. Comparisons are made between the food security status of different livelihood strategies identified during the course of the analysis.

Chapter three presents an overview of the design of an empirical ABM to explore food security of rural households within Malawi. A number of stages are covered as part of the development process, including: clarification of the model aim, conceptual model development, construction of the ABM and its validation and verification. Attention is given to ways to overcome data scarcity at the village level. The model is used to explore the impact of population growth and increased rainfall variability upon the availability, access, utilisation and stability of food over time.

Chapter four evaluates the potential of the ABM to identify pathways towards zero hunger. Techniques from EMA are adopted to investigate synergies and trade-offs between productivist, nutritionist and social protection strategies over time. A number of potential pathways towards zero hunger by 2030 are identified. Further model runs using the parameters of interest enable the different pathways to be evaluated with regards to their ability to fulfil availability, access, utilisation and stability of food.

Finally, chapter five provides a discussion of points raised throughout the course of the thesis. In addition to the three objectives of the thesis, attention is given to the salience, credibility and legitimacy of the simulation tool. Concluding remarks reflect on the potential of agent-based modelling to unravel the complexity of household food security and consider its applicability within different contexts.

1.5 Literature Review

1.5.1 The Origins and Evolution of Food Security

Origins of the concept of food security can be traced back to the post World War I and World War II periods, when the international community began to collect national food balance sheet data (Kelly *et al*., 1991). Representing 'supply side data', food balance sheets quantify the availability of calories, based upon the quantity of food produced or imported into a country. At the time, this supported food allocation and distribution efforts in conflict-affected regions (Kelly *et al*., 1991). In 1948, the Universal Declaration of Human Rights recognised the right to food as a core element of an adequate standard of living (UN, 1948). The term 'food security' however, was not formally recognised until the early 1970s. A global food crisis between 1972 and 1974 resulting from climatic shocks and high food prices, led to concerns that global food supply shortages would threaten political stability (Timmer, 2010). Subsequently, the 1974 World Food Summit defined food security as ensuring *"availability at all times of adequate food supplies"* (UN, 1975).

The focus on food availability alone was criticised by Amartya Sen in his 1981 thesis: *"Poverty and Famines: An Essay on Entitlement and Deprivation"*. By providing historical examples of famine conditions in countries with sufficient quantities of national food supplies, Sen (1981) highlighted the fact that food availability was not adequate for ensuring household access to food. Under circumstances characterised by high food prices and low demand for wage labour, Sen (1981) argued that the poor may lack entitlements to food. Growing recognition of the need to take into account food access as well as food availability was reflected within the revised definition of food security in 1983. Here it was stated that food security also required "*physical and economic access to basic food*" (FAO, 1983).

Combined with ideas surrounding basic needs (Hicks, 1979; Streeten, 1980; Streeten, 1984), the entitlement approach shifted emphasis away from macro-level food security and towards greater consideration of the micro-level (Burchi and Muro, 2016). Issues surfaced regarding the equity of food availability and access at the household level. Studies of intra-household allocation uncovered cultural and social bias leading to age and gender preferences when distributing food (Deaton, 1987; Sen, 1990; Senauer, 1990). By the 1990s, concern was also mounting for greater nutrition and in particular, alleviating micro-nutrient deficiencies in the form of iron, vitamin A and iodine (Darnton-Hill, 1998; Nilson and Piza, 1998; Underwood, 1998; Yeung, 1998). Focus shifted away from caloric sufficiency towards overall diet quality (Welch and Graham, 1999). As a result, utilisation was incorporated as a third dimension of food security alongside availability and access. In addition to dietary quality, the concept of utilisation considers an individual's ability to prepare food (e.g. through access to potable water and cooking fuel) and absorb it (e.g. through consideration of their physical health) (Pinstrup-Andersen, 2009).

The multi-dimensional and multi-scalar nature of food security was captured in the definition issued by the 1996 World Food Summit. This defined food security as a state in which *"all people at all times have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life"* (FAO, 1996).

This definition of food security is widely used today and will be referred to throughout this thesis. In addition to the three dimensions of food security, namely availability, access and utilisation it acknowledges the ability to acquire socially and culturally acceptable foods. The phrase "*at all times"* also highlights the temporal aspect of food security and introduces a fourth dimension: stability. This dictates how robust availability, access and utilisation dimensions are to shocks and stresses over time (FAO, 2009). Exogenous factors such as population growth, climate change and political unrest may undermine the availability of food and the ability of households to access and utilise it (Godfray *et al*., 2010).

1.5.2 Complexity of Rural Food Security

Traditionally, social and ecological aspects of food security have been studied independently. However, there is a growing consensus that human and natural systems are inseparably linked and should be dealt with as social-ecological systems (Norström *et al*., 2014). Typically, humans interact with agricultural ecosystems to optimize outputs of food, fibre and fuel (Poppy *et al*., 2014). Sustainable, long-term provision of such benefits is dependent upon regulating ecosystem services including pollination, pest and water regulation (MEA, 2005). As a result of these processes, agriculture can continue to provide a host of regulating, provisioning and cultural services to communities (MEA, 2005).

Assumptions surrounding a stable and resilient environment however have tended to dominate perspectives within agricultural science and development programmes. The idea that flows of resources can be controlled and that removing human induced stressors can return nature to a steady state has proved persistent. Thompson *et al*., (2009) argue that a number of factors including climate change, population growth, shifts in land use and uncertain political and economic circumstances cause such narratives to be wholly inadequate. Greater understanding of coupled human and natural systems such as these, arises from the examination of how multiple parts interact and operate together, rather than the analysis of discrete elements in isolation (Liu *et al*., 2007).

With growing recognition of the need for a basis to better understand interactions between rural households, institutions and the environment (Ellis, 1998), the SLF was fully developed by DFID (1999). The framework recognises the multiple interactions between the various factors that affect livelihoods and emphasises the often complex nature of livelihoods (Chambers and Conway, 1991).

According to Berkes *et al*., (2008) a system is complex if it exhibits nonlinearity, uncertainty, emergence, scale and self-organization. Non-linearity is inherently linked to uncertainty. Solutions to non-linear equations produce large ensembles of possible values rather than simple numerical answers (Stogartz, 2014). These manifest in the form of multiple equilibria as opposed to one stable equilibrium (Bankes *et al*., 2003). Within rural systems, different livelihood strategies represent alternate stable states (Tittonell, 2014). Self-organisation occurs when complex systems assemble around one of several possible equilibrium states or attractors. To some extent, feedbacks present within the system attempt to respond to any changes in conditions to maintain the system within its current state. At certain thresholds, tipping points might be reached and system properties may change very rapidly (Scheffer and Carpenter, 2003). The dynamic nature of livelihood strategies causes agricultural systems to exhibit path dependency. The current status of the system is largely determined by the sequence of states that the system has gone through in the past (Tittonell, 2014).

Scale is an important feature of rural agricultural ecosystems. Decisions made by individual households that result from interplay between social, ecological and economic factors, can have emergent effects at village, regional and landscape levels (Wijk *et al*., 2012). This has been overlooked by current measures of food security which tend to draw attention to entire nations or individual households (Pinstrup-Andersen, 2009; Carletto *et al*., 2013). Community food security represents a recent concept that favours long-term systemic approaches to address food insecurity in an equitable and sustainable manner. In contrast to household or national food security, community food security emphasises the complex nature of food systems, which are nested within dynamic social, ecological and economic processes (Thompson and Scoones, 2009; Kaiser, 2011). A renewed focus is given to interactions between system components such as households, institutions and the environment and the emergence of diverse food systems and food security outcomes (Hamm and Bellows, 2003; McCullum *et al*., 2005).

Berkes *et al*., (2008) highlight three consequences arising from the nature of complex systems. Firstly, the inadequacy of models grounded on linear thinking. Secondly, the need for mixed methods approaches combining both qualitative and quantitative data and thirdly, the importance of using a multiplicity of perspectives. The remainder of this literature review will consider how agent-based modelling may address these three key issues. I begin by briefly considering why modelling is worthwhile, before discussing different modelling techniques and highlighting the need for non-linear models to better understand complex systems.

1.5.3 The need for non-linear models

The purpose of modelling is manifold (Epstein, 2008). According to Matthews (2012), the primary function of models is as an aid to research. When in pursuit of greater clarity of real-world systems, simulation tools promote abstraction and formalisation of ideas (Sterman, 2002). Indeed, model development dictates that researchers make interactions and assumptions implicit in mental models, more explicit (Epstein, 2008). Simulation tools also assist with the integration of theories across different disciplines and form virtual laboratories offering low-risk environments to test ideas (Wainwright and Mulligan, 2012). Under circumstances whereby manipulation of real-world systems is too costly, disruptive or unethical, computer models can be of great use (Peck, 2004).

The process of constructing and analysing models can also generate new research questions and highlight research gaps. If a simulation tool incorporating current theory is unable to generate the expected responses, there may be knowledge gaps to fill (Boone and Galvin, 2014). By taking into account the sensitivity of model outputs to parameter uncertainty, simulation tools can be used to direct field data collection activities (Wainwright and Mulligan, 2012). Finally, modelling can also assist with policy formulation and the management of complex systems (Verburg *et al*., 2015). Brown *et al*., (2013) identify a number of phases of the policy cycle that may be addressed by different types of models and/ or model applications. A review of land use models found simulation tools may play an important role during problem identification, intervention design, ex-ante assessment, and ex-post assessment (Brown *et al*., 2013).

Despite these advantages, simulation tools have also been met with some criticism (Hess, 1996; Winsberg, 1999; Heckbert *et al*., 2010). Regarding numerical models, Oreskes *et al*., (1994) highlight the fact that they are frequently misinterpreted. Often, the predictive power of numerical models is exaggerated. The outputs of simulations may be used as a basis for public policy decisions with little consideration given to model uncertainty (Oreskes *et al*., 1994). Problems associated with the verification and validation of such models are also suggested (Oreskes *et al*., 1994). Furthermore, Berryman (1991), argues that the data-heavy nature of simulation tools often causes them to be costly and inefficient. As a result of the sequential nature of model procedures, redundant equations can also cause the inaccuracy of simulation tools to grow exponentially over time (Berryman, 1991).

However, when constructing models, it is important to bear in mind that *"all models are wrong, but some are useful"* (Box and Draper, 1987, p.424). Indeed, Levins (1966) recognised that models represent a trade-off between reality, generality and precision. In this context, reality refers to how well the model structure reflects real-world processes and mechanisms (Levins, 1966). Generality considers the extent of the model scope. It reflects how many different kinds of situation the model could be usefully applied to (Levins, 1966). Finally, precision evaluates the accuracy of model outputs (Levins, 1966). Simultaneously maximising the realism, generality and precision of a model will hamper the ability to build and make use of the model effectively (Bullock, 2014). In the remainder of this section I consider how useful different modelling techniques are to the study of complex social ecological systems, and in particular, to the study of rural food security.

1.5.3.1 Mathematical Programming

The application of mathematical programming techniques to smallholder decision-making dates back to at least the 1950s (Loftsgard and Heady, 1959). When solving farm planning problems, linear programming (LP) methods were practised routinely (Van Wijk *et al*., 2014). Such optimisation models are based on the specification of behavioural assumptions like profit maximisation and can be employed to solve optimal resource allocations which are subject to constraints (Low, 1974).

Mathematical programming was utilised by Dorward (2003) to investigate the impact of policy and development interventions in promoting pro-poor agricultural growth within Malawi. Attention was given to interventions surrounding maize prices, the provision of input subsidies, reduction of marketing costs and adoption of cash transfers (Dorward, 2003). Equations underpinning the model maximise expected utility, describe constraints to resource use and production opportunities, as well as outlining upper bounds to activities such as the sale of labour and consumption of hybrid maize in the pre-harvest period (Dorward, 2003). Results highlighted the relative importance of both farm and non-farm activities to the livelihoods of the rural poor, as well as advocating pro-poor policy in the form of credit transfers to mitigate higher food prices, combined with either universal input distribution, input subsidies or maize price stabilization (Dorward, 2003).

According to Van Wijk *et al*. (2014), mathematical programming techniques harbour a number of advantages when modelling household decision-making. Typically, an optimisation model will produce the best possible results for a particular objective, e.g. energy maximisation or cost minimisation, under specified constraints (Van Wijk *et al*., 2014). Furthermore, when compared with alternative simulation approaches, optimisation models tend to be less data intensive (Van Wijk *et al*., 2014).

However, linear mathematical models fail to address many of the characteristics of complex systems. Berger (2001), acknowledges that a major weakness of the approach is its failure to explicitly capture interaction between the agents in the model. As a result, it is hard to portray the emergence of system behaviour at multiple levels. Feedbacks between components are also difficult to model effectively (Van Wijk *et al*., 2014). In some instances, the assumption that households make optimal decisions may also be an oversimplification (Barlett, 1984).

The inadequacy of models based on linear thinking to portray the true nature of complex systems combined with the advent of accessible computational power has led to new approaches. In the following section, I consider the potential of two further simulation tools, namely systems dynamics modelling and agent-based modelling.

1.5.3.2 Systems Dynamics Models

In contrast to linear models, systems dynamics models are frequently used to capture feedback loops. Within dynamic simulation models, spatial and temporal aspects of system behaviour are incorporated through the use of either ordinary or partial differential equations (Leffelaar 1999). It is a top-down modelling technique in which the system of interest is studied in terms of stocks and flows that interact through feedback loops (Meadows, 2008).

The Pastoral Household and Economic Welfare Simulator (PHEWS) is an example of a dynamic simulation model, constructed by Thornton and Herrero (2001). A simple rule-based approach was employed to develop the household model, which comprises of stocks of livestock, flows of cash and dietary energy. PHEWS was integrated with an existing spatial-dynamic ecosystem model, SAVANNA and calibrated for the Ngorongoro Conservation Area (NCA) in northern Tanzania (Thornton and Herrero, 2001). Simulation of two population growth scenarios highlighted the dependence of NCA households upon exogenous sources of calories and revealed severe pressures on pastoralist welfare under current human population densities (Thornton and Herrero, 2001).

A further systems dynamic simulation based upon allocation of household resources is described by Tittonell *et al.*, (2009). Here, a crop/ soil dynamic simulation model is combined with a mathematical model to identify farming strategies that provide optimal trade-offs between different farming objectives (Tittonell *et al*., 2009). Application of the integrated model, parameterised for Mutsulio village in western Kenya, found small investments in nutrient inputs could double maize yields. Such intensification of the system could be achieved so long as there was adequate labour to ensure efficient nutrient capture and conversion to maize yield (Tittonell *et al*., 2009). However, oversimplifications of the model may have caused the impact of socio-economic constraints on fertiliser use to be neglected. Disparities between observed and predicted yields were attributed to the lack of consideration given to access, labour and/ or knowledge limitations (Tittonell *et al*., 2009).

Key strengths of the systems dynamics technique are its ability to take into account both spatial and temporal aspects of system behaviour, as well as the relative ease of model construction and validation with available data (Van Wijk *et al*., 2014). Systems dynamics can be useful within participatory settings, as a tool to translate complex mathematical concepts into stocks and flows etc. that can be clearly visualised and may be easier to understand (Tidwell *et al*., 2004). In addition, the simulation methods are regarded to be computationally efficient (Van Wijk *et al*., 2014). Potential pitfalls however, are linked to underlying assumptions of the technique, including: the presence of a homogenous and well-mixed population, that mathematical equations can capture all feedback structure in the system and that macro-level behaviour is independent of micro-level behaviour (Parunak *et al*., 1998).

1.5.3.3 Agent-based Models

Agent-based modelling is a bottom-up technique in which interactions between individual agents at the local level, lead to emergent, aggregate behaviour at the macro-level (Farmer and Foley, 2009). Characteristically, ABMs comprise of multiple autonomous agents, a common environment and a set of rules underpinning the interactions between the agents and their environment

(Matthews *et al*., 2007). The SimSahel model (Saqalli *et al*., 2011; Saqalli, 2008) is one example of an empirical ABM employed at the household level. All stages of model construction and validation utilised data gathered from household surveys and PRA exercises (Saqalli, 2008). Simulations of different scenarios evaluated the impact of development interventions on the population of three Nigerien villages that differ in terms of their socio-economic and ecological contexts (Saqalli *et al*., 2011).

Similarly, SAMBA-GIS is an agent based model built and employed by Castella *et al*., (2005) to explore land use changes in the northern mountains of Vietnam. The model was constructed empirically, through the use of a role-playing game (Castella *et al*., 2005). Participants took the place of farmers, basing land use decisions on their ability to fulfil the rice needs of their families (Castella *et al*., 2005). Decisions of participants informed the behavioural rules of virtual agents within the ABM. Simulations of different scenarios were employed to evaluate the impact of land use change upon the natural resource base (Castella *et al*., 2005).

The heavier development and data costs associated with empirical ABMs are considered an inevitable downfall of this technique (Van Wijk *et al*., 2014). Simulations of complex phenomena involve the estimation of numerous parameters and sourcing adequate data may be challenging (Van Wijk *et al*., 2014). In addition, Grimm *et al*., (1999) concede that ABMs are in general, more difficult to analyse. Despite this, a number of characteristics inherent to agent-based modelling cause it to be an ideal tool for simulating rural food security. Agent-based simulations enable the heterogeneous nature of households, individuals and the environment to be taken into account (Epstein, 1999). ABMs also employ a dynamic approach that allows the trajectory of households and individuals to be traced over time (Valbuena et al., 2008; Valbuena *et al*., 2009). A key advantage of the technique is its ability to represent decision-making and behaviour (Smajgl *et al.*, 2011; Smajgl and Bohensky, 2013). The behaviour of an agent is in part determined by that of others. As a result behaviour cannot be deduced a priori, nor is it easy to solve – it must be simulated.

1.5.4 Representing decision-making and behaviour

An underlying assumption of linear models is rational behaviour. Here, endowed with clear preferences and all available information, a rational agent, *homo economicus* will always elect the optimum solution with no associated cost (Gigerenzer and Todd, 1999). Under the guise of rationality, agents are often considered to act to optimise a utility function, where utility is the ability of something to satisfy needs or wants (Monticino *et al*., 2007). By mapping the expected utility value of every available state (or action) it is possible for agents to select the most optimal course by objectively ranking the value of each state (Monticino *et al*., 2007).

Mathematical modelling in the form of linear programming may be used to model such unbounded rationality (Gigerenzer and Todd, 1999). Here, a utility function combined with a set of linear constraints, is considered to constitute an optimisation problem (Dantzig, 2002). The set of variables that maximise (or minimise) the value of the utility function constitute the solution. It is the maximum (or minimum) value of the utility that corresponds to the optimal solution (Dantzig, 2002).

A study by Dorward (1991) provides an example of where this technique has been applied to model the behaviour of Malawian small holders. In this case, the subsistence production goals and cash income objectives of households were modelled using linear programming (Dorward, 1991). Once subsistence goals had been met households selected cash crops in two stages. First, crops requiring more investment than could be supported by current grain and cash stocks were disregarded (Dorward, 1991). Subsequently, from the remaining cash crops a selection was made based on cash margin per hectare, or per man-hour of planting and weeding labour (Dorward, 1991).

A common criticism of rational models of decision-making is the treatment of the mind as a Laplacean Demon, armed with infinite time, knowledge and computational prowess (Gigerenzer and Goldstein, 1996). Barlett (1984) argued that farmers are seldom efficient maximisers. Furthermore, linear programming models were criticised by Gladwin (1989) for not being empirically grounded. A review of 48 bio-economic farm models found only 23 authors reported having carried out some form of comparison with actual farming practices (Janssen and Van Ittersum, 2007). Of these, only 4 made quantitative comparisons between model outputs and real-world data (Thompson and College, 1982; Schilizzi and Boulier, 1997; Ramsden *et al*., 1999; Vatn *et al*., 2006). Rather than adopting a positive approach to decision-making in which the actual responses of farmers are modelled in an attempt to better understand behaviour (Howitt, 1995), the majority of linear models were found to favour the normative approach in which simulations are used to help identify how farmers should behave in order to manage resources most effectively (Janssen and Van Ittersum, 2007).

Agent-based modelling provides a means to depart from the notion of rational, normative agents. A number of decision architectures have been developed to take into account bounded rationality, a concept first expanded upon by Simon (1955). Here, agents possess neither the information to compare all feasible alternatives, nor the computational power to select the optimum (Simon, 1955). Techniques such as fast and frugal heuristics (Gigerenzer and Gaissmaier,

2011) and fuzzy logic (Zadeh, 1996), which can be easily implemented within ABMs, underpin the approach.

According to Gigerenzer and Gaissmaier (2011, p.454) a heuristic is *"a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally and/ or accurately than more complex methods"*. Studies such as that by Kalanda-Joshua *et al*., (2011) compound the view that farmers tend to employ a large number of heuristics. Farmers in Nessa Village, Malawi for example, interpret the behaviour of animals, birds and insects as indicators of future weather (Kalanda-Joshua *et al*., 2011). Sightings of the bird nanzeze (*Glareola nordmanni*) announce the arrival of rain in less than a week, while the distinct sound of croaking frogs suggest rains are imminent (Kalanda-Joshua *et al*., 2011). A further study by Roncoli *et al*., (2002) documents the use of plant phenology and the movements of the moon to predict seasonal rainfall in Burkina Faso. Of 23 farmers surveyed, the majority were able to forecast a 'good' rainy season for 1998 using environmental observations and predictions from ritual specialists (Roncoli *et al*., 2002). Such indigenous knowledge can equip smallholders with simple, but effective rules of thumb. In Ghana for example, farmers consider five days of consecutive rain to announce the start of the rainy season, after which they commence cultivation of fields (Schreinemachers and Berger, 2006).

In order to describe the bounded nature of heuristic agents, Simon (1976) coined the term 'satisficing', an amalgamation of the two words: satisfying and sufficing. Acknowledging costs associated with solution finding, satisficing agents exhibit limited search, instead preferring to settle quickly upon a solution deemed 'good enough' (Simon, 1976). Implementation of satisficing agents can be achieved by first selecting an aspiration at or above which a solution is considered 'good enough' (Slote and Pettit, 1984). Until a solution is found that satisfices the stated aspiration level, each of the potential solutions are evaluated in some unspecified order (Slote and Pettit, 1984).

Implementation of fast and frugal heuristics can be achieved through the use of decision trees. From a large solution set, a divide and conquer strategy can be employed to quickly eliminate undesirable solutions (Quinlan, 1990). Rather than a single solution, movement through a decision tree initiates a set of actions resulting from a series of choices and circumstances (Gigerenzer and Todd, 1999). A study by Deadman *et al*. (2004) provides an example of where decision trees have been used to instil agents with heuristic behaviour. Deadman *et al*. (2004) describe LUCITA, an agent-based simulation of land-use change in the Amazon rainforest. Three basic decisions regarding subsistence requirements, endowments and soil quality underpin household decision-making in LUCITA (Deadman *et al*., 2004). The resulting decision tree can be programmed using simple if-then decision rules (Fig. 1.5).

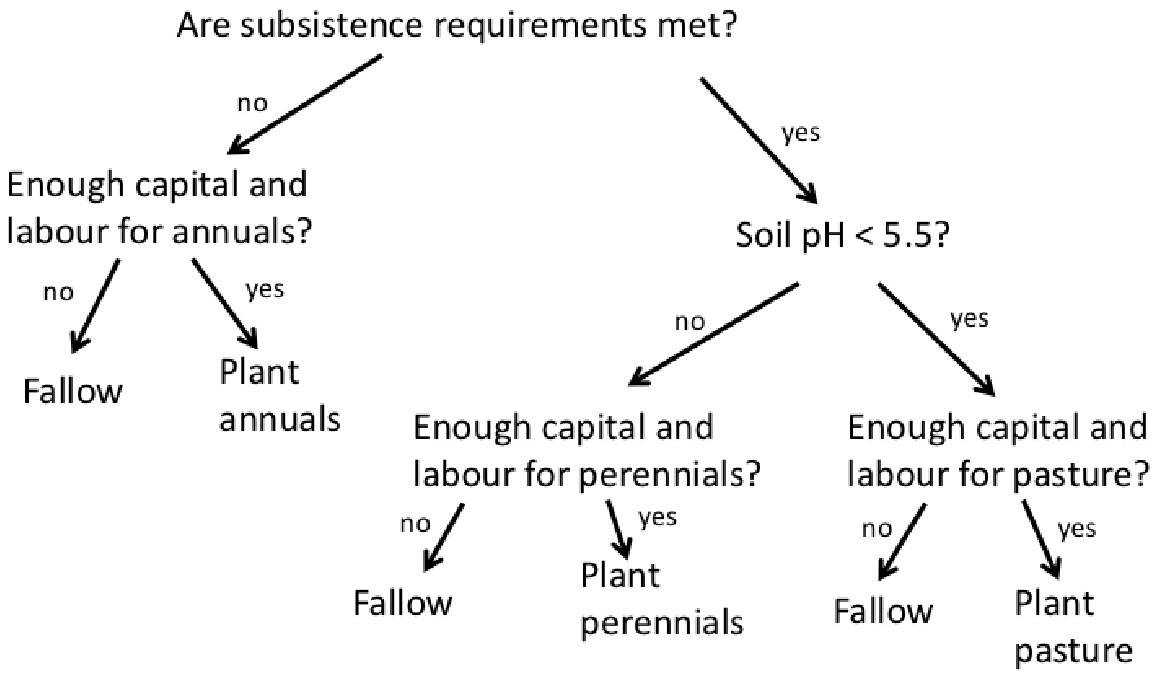

Figure 1.5: Example implementation of fast and frugal heuristics in the LUCITA model using a decision tree. Agents make three basic decisions surrounding household subsistence requirements, endowments and soil quality; taken from Deadman *et al*. (2004).

Heuristic decision-making can also be modelled using fuzzy logic. A recent study by Bosma *et al*. (2010) highlights the potential role of fuzzy logic as a framework to model heuristic decision-making. Interviews with stakeholders provided linguistic statements in the form of IF-THEN rules (Bosma *et al*., 2010). Such rules formed the foundation of a fuzzy logic model with which the decisions of farmers in the Mekong Delta could be explored (Bosma *et al*., 2010).

The concept of fuzzy logic, can be summarised simply as a "*method that interprets values in the input vector and based on some set of rules, assigns values to the output vector*" (Wang, 1998, pp. 2-18). In order to do this, input variables are first selected and fuzzified into a number of fuzzy sets or linguistic variables (Wang, 1998). Fuzzy sets were first introduced by Zadeh (1965) and represent an extension of classical set theory. Rather than crisp sets with defined boundaries, fuzzy sets describe vague concepts (Wang, 1998). A membership value between 0 and 1 reflects the degree to which an element belongs to a fuzzy set (Adriaenssens *et al*., 2004). The membership value an element takes is governed by the membership function associated with the corresponding fuzzy set. A series of IF-THEN rules are used to connect the input variables to the output variables using a fuzzy rule-based system (Wang, 1998).

A fuzzy rule is composed of two parts: firstly, an 'antecedent' referencing the state of the input variables and secondly, a 'consequent' describing the corresponding values of output variables (Adriaenssens *et al*., 2004). In Mamdani-Assilian models, the degree to which each part of the antecedent has been satisfied can be evaluated once the input variables have been fuzzified (Adriaenssens *et al*., 2004). Outputs from the consequents of all rules are then aggregated to produce one fuzzy set for each output variable (Adriaenssens *et al*., 2004). The order in which the rules are evaluated has no effect on the end result, so long as a cumulative method is employed for aggregation (Wang, 1998). As the resulting aggregate of a fuzzy set constitutes a range of output variables, it must be defuzzified to yield a single, crisp output variable from the set (Wang, 1998). In order to do this, the centroid calculation is frequently employed (Bosma *et al*., 2010). Following defuzzification, the decision model can be validated and optimised (Bosma *et al*., 2010).

According to Zadeh (1996), the strength of the fuzzy logic approach lies in its use of natural language. Typically, *in silico* computations favour the manipulation of numbers and symbols, whereas human computing and reasoning has relied upon words (Zadeh, 1996). Within fuzzy inference systems however, complex relationships between attributes and descriptors can be captured using linguistic expressions in a descriptive and transparent manner (Mackinson, 2001). Furthermore, fuzzy logic provides a mechanism through which qualitative and quantitative knowledge can be combined (Mackinson, 2001). Despite such advantages, a distinct lack of formal methods with which to define membership functions represents a key weakness of the approach (Bosma *et al*., 2010). Additions to the variable set also cause the number of fuzzy rules to increase exponentially (Setnes, 2001).

1.5.5 The importance of mixed methods approaches

The ability to combine both qualitative and quantitative approaches within ABMs is a further strength of the simulation tool (Yang and Gilbert, 2008). Until recently, a lack of accessible computational power caused formal models based upon quantitative data to be favoured (Edmonds, 2015). Qualitative evidence has often been criticised by the scientific community for being subjective, biased, unreliable and context specific (Morse, 1999). However, Edmonds (2004) argues that quantitative representation may not always provide the best method. Careless or inappropriate use of quantitative data can distort the phenomenon of interest, lead to the accumulation of error and create artefacts (Edmonds, 2004).

When dealing with complex systems, non-linearity means that there are many possible solutions rather than a single, numerical answer (Berkes *et al*., 2008). As a result, simple quantitative analyses are not very helpful. Instead there is a need for mixed methods approaches that allow quantitative and qualitative data to complement one another. There are a number of stages throughout the model design, implementation and validation process, which benefit from the incorporation of qualitative data. Elsawah *et al*. (2015) describe the use of cognitive maps as a starting point for the development of an ABM exploring water resource management in South Australia. Qualitative perceptions of stakeholders were integrated into a formal simulation model using a causal mapping technique. This was followed by time-sequence diagrams to structure the decision-making process (Elsawah *et al*., 2015). In order to validate an ABM of land use change in the Netherlands, Ligtenberg *et al*. (2010) used results from a role-playing game. Participant sketches of preferred locations for urban development were compared with model outputs (Ligtenberg *et al*., 2010).

A common theme underlying these studies is the use of participatory approaches. Decision makers and/or stakeholders are not necessarily limited to be the end users of models. According to Lynam *et al*., (2007, p.4), interaction between scientists and stakeholders may entail extractive use whereby *"knowledge values or preferences are synthesised by scientists and passed on as a diagnosis to a decision-making process"*. Dobbie *et al.* (2015) for example, describe the indirect involvement of stakeholders throughout the construction of a simple ABM investigating the seasonality of rural livelihoods in Malawi. Outcomes from interviews and participatory rural appraisal (PRA) exercises were used to inform simple behavioural rules of household agents (Dobbie *et al*., 2015). The resulting model was used to explore the effect of drought upon activity preference and food security over time (Dobbie *et al*., 2015).

Aside from extractive use, interaction between scientists and stakeholders may elicit co-learning, where, *"syntheses are developed jointly and the implications are passed to the decision-making process"* (Lynam *et al*., 2007, p.4). Naivinit *et al*. (2010) document the use of a role playing game to co-design an ABM of rice production and labour migrations in Northeast Thailand. Members of households residing in the Lam Dome watershed were invited to attend village-based modelling workshops (Naivinit *et al*., 2010). Iterative role playing games were employed to construct an ABM progressively in a collaborative manner (Naivinit *et al*., 2010).

Finally, the premise of participatory modelling may permit co-management, in which *"the participants perform the syntheses and are included in a joint decision-making process"* (Lynam *et al*., 2007, p.4). A study by Becu *et al*. (2008) investigated the potential for comprehensive involvement of stakeholders throughout the modelling process. When constructing an ABM of watershed conflict in Northern Thailand, stakeholders were engaged in the assessment of model assumptions, scenario design and interpretation of results (Becu *et al*., 2008).

1.5.6 The importance of using a multiplicity of perspectives

Drawing on a multiplicity of perspectives is essential when analysing or managing complex systems (Berkes *et al.*, 2008). The multi-scalar nature of food security means there is no single perspective that will adequately capture all of its inherent complexity (Maxwell *et al.*, 2014). Grand challenges such as food security typically arise in systems with a multitude of components that interact using a variety of mechanisms which can only be partly observed (Hammond and Dubé, 2012). The term dynamic complexity refers to the sometimes surprising and counter-intuitive behaviour that can arise within systems as a result of non-linearity and the interactions and feedback loops between system components (May and Oster, 2011). This poses problems for the management of systems, as changes in one process may be resisted (or even reversed) by adaptive responses elsewhere in the system (Hammond and Dubé, 2012). Likewise, synergies and feedbacks between components which could have advantageous outcomes might remain unnoticed by decision makers (Hammond and Dubé, 2012).

In some cases, model builders may not know or agree on key drivers responsible for shaping the future, the probability distributions underlying important variables and/ or the significance of different outcomes (Lempert *et al*., 2003). The inability of modellers to order such alternate realities based on how likely or plausible they are may be symptomatic of conditions of deep uncertainty (Kwakkel *et al*., 2010).

Application of predictive models under conditions of deep uncertainty is highly problematic (Bankes, 1993). It has led to criticisms such as "*the forecast is always wrong"* (Ascher, 1978, p.125) and resulted in extensive debate as to whether (or not) models amount to 'useless arithmetic' (Pilkey and Pilkey-Jarvis, 2007; Arhonditsis, 2009). To better understand complex problems, there is a need to explore the effect that different model formulations and variations in model parameterisation have upon the behavioural dynamics and outcomes of simulations (Kwakkel and Pruyt, 2013). EMA uses specific search strategies to construct a suite of models that are consistent with the available information (Agusdinata, 2008). Together, the models provide a set of plausible futures to explore (Agusdinata, 2008).

When constructing the ensemble of models using EMA, two types of search strategies can be distinguished: open exploration and directed search (Kwakkel and Pruyt, 2015). For the former, the aim is to generate a set of models that cover the entire uncertainty space. Exploration relies upon sampling techniques such as Monte Carlo Sampling (Shapiro, 2003), Latin Hypercube sampling (Helton and Davis, 2003) or factorial methods (Agusdinata, 2008). When attempting to manage complex systems, open exploration can help address questions such as under what circumstances would this policy do well? And under which conditions would it be likely to fail? (Kwakkel and Pruyt, 2015). The second type of search strategy, directed search, finds specific cases that are of interest. Using optimising techniques such as genetic algorithms (Mitchell, 1998), directed search generates insights from specific areas of the uncertainty space. Using this approach, the analysis may be used to answer such questions as: what is the worst that could happen? And what is the best that could happen? (Kwakkel and Pruyt, 2015).

Agent-based modelling provides a vehicle to conduct EMA. Studies by Kwakkel and Pruyt (2013) and Yücel and Van Daalen (2011) have described the application of EMA using ABMs of energy transition and innovation diffusion, respectively. A total of 13 uncertainties surrounding investment costs, operation costs and energy demand amongst others, are explored by Kwakkel and Pruyt (2013). A classification tree is then used to uncover how the uncertainties jointly affect the transition towards more sustainable energy generation (Kwakkel and Pruyt, 2013). The tree provides a clear visualisation of results, which demonstrate that in most cases, the proportion of energy from fossil fuels is greater than renewables (Kwakkel and Pruyt, 2013). This led Kwakkel and Pruyt (2013) to conclude that current efforts would not be sufficient to promote transition towards more sustainable energy generation as existing policies are not effective across a large portion of the uncertainty space.

In conditions dominated by uncertainty, a focus on robust, rather than optimal policies is a common theme that has surfaced from exploratory modelling techniques. A number of definitions of robustness exist, but the notion of satisficing over numerous plausible future states of the world is a unifying feature (Lempert *et al*., 2003; Haim, 2006). Weaver *et al*. (2013) argue that narrow conceptualisations regarding the application of climate models have previously hindered the potential of such simulation tools to inform decision-making. By envisioning climate models as scenario generators and sources of insight into complex behaviour, however, it may be possible to overcome the 'predict-then-act' dogma (Weaver *et al*., 2013). Indeed, Hall *et al*. (2012) document the identification of robust climate policies under uncertainty. Risk averse policies were found to perform best when compared with business as usual scenarios (Hall *et al*., 2012).

In order for the results of EMA to be of use to decision makers, the underlying ABM must be salient, credible and legitimate (Weichselgartner and Kasperson, 2010). To be salient, the model and its outputs must be judged appropriate for the policy question(s) of interest and be readily accessible and comprehensible by decision makers (Mcnie, 2007; Weichselgartner and Kasperson, 2010). To be credible, underlying model uncertainty and validity must be communicated effectively. To be legitimate, realistic solutions must be provided that can be implemented in a timely manner (Bradshaw and Borchers, 2000). The following section will provide an introduction to the case study area of rural Malawi.

1.5.7 Introduction to the Case Study

Malawi is a small, landlocked country within Sub Saharan Africa that borders Zambia, Tanzania and Mozambique. Home to approximately 16 million people, Malawi has a rapidly expanding population, which is increasing at the rate of 2.8% per year (UN, 2015a). A low-income country, Malawi ranked 173 out of 188 within the 2015 UNDP Human Development Index (UNDP, 2015). In 2014, the government of Malawi reported over 50% of its population to be living on less than 1 USD per day (Gondwe, 2014). The country is divided into Northern, Central and Southern administrative regions. Malawi has 28 districts: 6 in the Northern, 9 in the Central and 13 in the Southern region, respectively. The districts are governed by Traditional Authorities, presided over by chiefs, and are composed of villages. Villages represent the smallest administrative unit and are led by village chiefs and heads.

Agriculture remains the most important sector of the economy, responsible for employing 80% of the workforce (NSO, 2012a). Estates and smallholder farmers comprise a dualistic sector (Lele, 1990). Free-hold or leasehold tenure is common for estate land, where tobacco, tea, sugar and coffee constitute the main crops (Lele, 1990). In terms of export, tobacco provides the largest export cash crop for Malawi. In 2014 it accounted for over 50% of export earnings, followed by sugar and tea (NSO, 2015).

1.5.7.1 Livelihoods of Rural Households

In spite of rapid increases in the size of the urban population, Malawi is still a predominantly rural country. In 2014, more than 84% of Malawians lived in rural areas (UN, 2015c). The vast majority of the rural population are smallholder farmers where customary tenure dominates (NSO, 2012a).

Self-sufficiency in maize production is a key priority for the majority of smallholder households (Chibwana *et al*., 2012). It is the main ingredient for a meal porridge termed ‘nsima’, which constitutes the staple diet of rural households (Patel *et al*., 2015). Supply shortages and high prices make it difficult for households to purchase maize during the lean period of January to March (Takane, 2013). In a bid to ensure their consumption needs are met, rural households therefore grow as much maize as possible (Chibwana *et al*., 2012).

Despite such an emphasis upon maize production, a study by Takane (2013) found that sampled households in southern, central and northern Malawi fall short of self-sufficiency on average.

Households in Southern Malawi were least sufficient in maize, producing just 64kg per adult equivalent unit compared to the minimum requirement of 200kg (Takane, 2013). In general, it was found that households applied a mean of 71kg of fertiliser per hectare to maize (Takane, 2013), less than a third of the amount recommended by Langyintuo (2004). All in all, leading the authors to conclude that a lack of credit for maize production meant smallholder famers were unable to afford the recommended inputs, limiting potential yields (Takane, 2013).

Although government liberalisation policies in the early 1990s meant smallholder burley tobacco production became a new economic opportunity (Van Donge, 2002), a number of entry barriers to growing the cash crop exist. When compared to maize production, tobacco is much more labour intensive, often requiring farmers to hire labourers (Takane, 2005; Takane, 2013). Inputs in the form of seeds, fertiliser, manure and materials for barns and bales mean production costs are high (Takane, 2005; Takane, 2013). Although these costs may be offset by high net income per hectare, there are substantial risks associated with tobacco production (Masanjala, 2006). Crop failure and unstable market prices can lead to substantial losses (Masanjala, 2006). A recent survey 685 tobacco farmers by Makoka *et al*. (2016) found that the economic costs of tobacco growing left rural households with minimal profits and in some instances economic losses.

Engaging in off-farm economic activities can reduce the dependence of rural households upon agriculture, which is predominantly rainfed (Masanjala, 2006). Takane (2013) identifies three key categories of off-farm income: firstly, agricultural wage income; secondly, non-agriculutral wage income; and thirdly, self-employed income. Issues surrounding agricultural wage income are debated throughout the wider literature (see Kerr, 2005; Bryceson, 2006; Orr *et al*., 2009). Frequently termed, 'ganyu', it refers to payments in cash or kind that result from temporary labour contracts for unskilled agricultural work (Whiteside, 2000). Non-agricultural wage income is hard to come by (Takane, 2013). Self-employed income however, is more lucrative, with households found to engage in beer brewing, basket weaving, brick making and sale of alcoholic drinks (Coulibaly *et al*., 2015).

1.5.7.2 Vulnerability of Rural Households to Food Insecurity

With the majority of livelihoods dependent on rain-fed agriculture, the population is vulnerable to the effects of natural disasters including droughts and floods (Sahley *et al*., 2005). In 2015, Southern Malawi experienced particularly severe floods, affecting as many as 1 million people (GoM, 2015a). High food prices and insufficient food production resulting from prolonged dry spells and/or flooding act to undermine the realisation of food security (Ellis and Manda, 2012). Rural farmers tend to live in remote areas with poor road access and limited means of transport

(Porter, 2014). Restricted access to markets and services acts as a constraint, minimising economic opportunities (Porter, 2014).

According to the National Census of Agriculture and Livestock (NACL) only 3% of smallholders were credit beneficiaries during the 2006 to 2007 growing season (NSO, 2010). Of those that were able to access it, only 1% received credit through a formal lending agency or bank, the majority being supplied by Non-governmental Organisations (NGOs) instead (NSO, 2010). Illness or injury is also very common. Results of the NACL found 53% of households in the smallholder sector had at least one member suffering from malaria and 30% had one or more members suffering from HIV/AIDS, with figures of 26% for asthma and 9% for tuberculosis (NSO, 2010). Shocks often force households to sell assets, hampering efforts to carry out productive activities (Dorward *et al*., 2009). As a result, poor households have to adopt coping strategies such as withdrawing children from school and reducing food consumption (NSO, 2012a).

Progress towards meeting the Millennium Development Goals (MDGs) within Malawi has been slow. A report by the Ministry of Finance, Economic Planning and Development in 2014 found half of the targets were unlikely to be met (Gondwe, 2014). Eradicating extreme poverty and hunger was the concern of Goal 1 of the MDGs. Within Malawi, the proportion of undernourished people rose from 22% in 2005 to almost 26% in 2013, failing to meet the MDG target of 11.8% (Gondwe, 2014). At the regional level, the proportion of undernourished people (defined as the proportion of population below the minimum level of dietary energy requirement) was highest within Southern Malawi at approximately 34.2% (Gondwe, 2014).

There is also growing concern regarding the prevalence of micronutrient deficiencies. A household survey in 2009 uncovered a high prevalence of anaemia within Malawi (GoM, 2009). Children under the age of 5 years old had the highest prevalence at 54.8% of the population, followed by non-pregnant women (32.0%) and school-aged children (25.4%) (GoM, 2009). The 2015 Cost of Hunger in Africa report, uncovered 10.3% of GDP within Malawi is lost annually to child undernutrition (GoM, 2015b). Over 23% of all child mortality cases were also found to be associated with undernutrition (GoM, 2015b).

1.5.7.3 Policies to Address Food Insecurity

Since the 1990s, in order to address food insecurity and poverty, the Government of Malawi has prioritised agricultural development. In 1998, the Malawi 2020 vision was adopted to provide a framework to implement short and medium-term plans for development sectors. This vision was later built upon by three overarching policy frameworks, including: The Malawi Growth and

Development Strategy I and II (from 2006-2011 and 2011-2016, respectively) (GoM, 2007), The Economic Recovery Plan 2012 and the National Export Strategy 2013-2018 (GoM, 2012).

More recently, the agricultural priority underlying each of the policy frameworks was deciphered into a series of sector-specific strategic documents. These documents include the National Agricultural Policy Framework 2010-2016 (GoM, 2011c), the National Irrigation Policy and Development Strategy 2010 (GoM, 2010) and the Agricultural Sector Wide Approach (ASWAp) 2010 (GoM, 2011a). The ASWAp outlines a single comprehensive priority programme and budget framework for the agricultural sector based on the agricultural priority of the MDGs which is also compatible with the Comprehensive African Agricultural Development Programme (CAADP) (GoM, 2011a). In agreement with the Maputo Declaration and CAADP, the ASWAp sets an annual growth target of 6% for the agricultural sector (GoM, 2011a). Existing sub-sectoral programmes were aligned with ASWAp. These include the Farm Input Subsidy Program and the Green Belt Initiative, which focus on the operationalisation of input subsidies and the sustainable management of land and water, respectively (FAO, 2015b).

Productivist strategies such as these reflect the belief that increasing food production will solve food insecurity. Conceição *et al*. (2016) argue that realising the potential of agriculture is key to improving food security and reducing poverty within Africa. Gains in productivity are considered to encourage a virtuous cycle, generating farm employment opportunities, increasing purchasing power and enhancing infrastructure development (Conceição *et al*., 2016). Parallels are made to green revolutions in Asia, where rapid, science-based, small-holder focussed agricultural growth has been linked to greater food availability, economic growth and poverty reduction (Thirtle *et al*., 2003).

Despite this, there is scepticism that the model prescribed within Asia can be imitated by smallholder farmers in Africa. The realisation of increased productivity through a land-scarce labour-abundant model, characterised by enhanced technology supply and intensive input use, has been criticised by Nin-Pratt and McBride (2014). A study of agricultural intensification in Ghana uncovered no correlation between population density and input use intensity (Nin-Pratt and McBride, 2014). Furthermore, the persistence of high labour costs within areas of high population density was found to limit the adoption of labour intensive technologies rather than promote uptake (Nin-Pratt and McBride, 2014). Evenson and Gollin (2003) argue that Africa still has land to expand into and as a result there is less incentive to intensify.

This contrasts the Asian blueprint for agricultural growth which was founded upon the adoption of high yielding crop varieties combined with intensive use of inputs such as fertiliser and irrigation (Hazell 2009). Negin *et al*. (2009) suggest that emphasis placed upon food production throughout the Asian green revolution caused nutritional aspects of food security to be neglected. Combined, this has led to recommendations that a broader notion of food security be incorporated into a green revolution that is 'uniquely African' (Negin *et al*. 2009).

The New Alliance for Food Security and Nutrition signifies a joint commitment between the Government of Malawi, private sector and G8 members to build upon existing country development plans (DFID, 2013). It represents a controversial shift away from pledges founded upon government intervention in favour of private sector involvement to alleviate hunger and malnutrition (Patel *et al*., 2014). According to the New Alliance, the resources of donors are to be directed towards high-priority, high-impact investments within the ASWAp (GoM, 2014).

Alongside agricultural growth led strategies, the Malawi Growth and Development Strategy recognises social protection and management of nutrition disorders and HIV/AIDS amongst its six broad themes (GoM, 2007). Two additional sub-sectoral programmes are relevant to social protection, namely the Labour Intensive Public Works Programme and the Social Cash Transfer Programme (GoM, 2007). The objective of the Public Works Programme is to generate employment opportunities for income transfer through labour intensive activities that simultaneously act to build economic infrastructure. Activities include the construction, rehabilitation and/ or maintenance of rural roads and small irrigation systems (World Bank, 2009). In contrast, the Social Cash Transfer Programme targets ultra-poor and labour constrained households to receive unconditional cash transfers (Abdoulayi *et al*., 2014). These activities address the primary objective of social protection which is to minimise food poverty and to tackle vulnerability (Devereux, 2016).

According to Devereux (2016), social protection strategies can aid food security by stabilising and raising incomes, as well as enhancing social justice. Prior to agricultural reforms in the 1980s, social protection strategies were widespread throughout Africa (Devereux, 2009). Within Malawi, national grain reserves acted to stabilise food supplies (Chilowa, 1998). Food pricing policies were used to promote equity (Harrigan, 1988) and input subsidies were used to encourage adequate access to fertilisers (Harrigan, 2008). However, such social protection strategies came under scrutiny from donor agencies (Harrigan, 2003). They were criticised for being expensive, poorly targeted and for interfering with the development of markets (Harrigan, 2003). As a result, structural adjustment programmes led to the abolishment of grain reserves, the collapse of state marketing activities and the scaling back of input subsidies over time (Sahn and Arulpragasam, 1991).

The dismantling of social protection strategies throughout the 1980s had a negative impact upon the livelihoods and food security status of smallholders (Chilowa, 1998). By the early 2000s, disenchantment with the results of structural adjustment resulted in the convergence of a new social protection agenda (Merrien, 2013). In Malawi, a number of social protection instruments have since been introduced including weather indexed crop insurance (Giné and Yang, 2009), public works projects (Chirwa *et al*., 2002), school feeding schemes (Galloway *et al*., 2009) and more recently, cash transfers (Miller *et al*., 2011). These measures have provided partial protection from seasonal food price fluctuations and have helped mediate shocks and stresses to food supplies (Devereux, 2009). However, the potential benefit of social protection strategies to rural households has been undermined by a lack of long-term funding, inadequate coverage and inconsistent implementation (Devereux *et al*., 2008).

Alongside social protection, nutrition has been integrated into government policies and budgets. A Food and Nutrition Security Policy 2005 (GoM, 2005) and a National Nutrition Policy and Strategic Plan 2007-2012 (GoM, 2009a) are in place and due for revision. Under the National Nutrition Policy and Strategic Plan, a number of nutrition programs are implemented to address five outcomes: i) improved maternal nutrition and care; ii) improved infant and young child feeding practices; iii) improved intake of essential micronutrients; iv) prevention and treatment of common infectious diseases and v) improved management of acute malnutrition (GoM, 2009a). In 2011, Malawi joined the Scaling Up Nutrition (SUN) Initiative. SUN represents a global movement promoting improved education surrounding good feeding practices, the fortification of foods to tackle micronutrient deficiencies and greater access to clean water and sanitation (SUN Movement, 2014a). Within Malawi this has led to the development of the National SUN Nutrition Education and Communication Strategy (NECS) (GoM, 2011b). In order to prevent stunting, the strategy aims to prevent chronic undernutrition during the first 1000 days of a child's life (GoM, 2011b).

Coordination of nutrition commitments reflects a focus on community-based action. The National Nutrition Committee is the convening body that provides technical guidance on the implementation of the National Nutrition Policy across related sectors (SUN Movement, 2014b). The multi-stakeholder platform is replicated at the district and village level, with District Nutrition Coordination Committees, Village Development Committees and Community Leaders for Action on Nutrition groups (SUN Movement, 2014b).

Despite a strong political commitment towards agricultural growth, poverty reduction and food security, the prevalence of hunger remains high within Malawi (NSO, 2012a). The Hunger and Nutrition Commitment Index ranked Malawi third out of 45 developing countries in 2014 (Lintelo and Lakshman, 2015). Comparisons of 22 indicators, including government spending, status of safety nets and access to water and sanitation, demonstrated Malawi's 'high commitment' when compared with other developing countries (Lintelo and Lakshman, 2015). However, progress in reaching the MDG to eradicate extreme poverty and hunger, was found to be slow (Gondwe, 2014). In order to identify robust pathways towards zero hunger, there is a need to ensure the complexity of rural food security is addressed appropriately. To be effective, policies must be coherent. The impact of policies and development programmes must not undermine food insecurity (Brooks, 2014). Furthermore, coordination of policies across sectors must be mutually supportive as opposed to off-setting (Brooks, 2014). With this in mind, there is a need for novel tools to help navigate robust pathways towards zero hunger.

1.5.8 Current research gaps

Having set the context by introducing the complex nature of food security, the potential of agent-based modelling and the case study area, the remainder of this section will consider research gaps to be addressed throughout the course of the thesis. These are summarised for each of the three objectives in turn.

1.5.8.1 Identifying Livelihood Strategies of Rural Households

The food security status of households tends to be reported at the national or regional level (see FAO *et al*., 2015). Such aggregate measures fail to adequately capture variation between households. Disaggregating estimates based upon income and gender provides a more detailed picture (See NSO, 2012b). However, in order to tackle food security effectively, there is a need to better understand the underlying mechanisms that give rise to the aggregate outcomes (Thompson and Scoones, 2009). A further downfall of current measures of household food security, is the tendency to focus upon the availability of food (Headey and Ecker, 2013). This neglects issues surrounding food access, utilisation and stability and as a result, the multidimensional nature of household food security is seldom taken into account (Headey and Ecker, 2013). There is a need for new approaches to unpack the diversity of households and provide a more comprehensive analysis of food security.

Chapter two explores how this research gap can be overcome. By operationalising the SLF it could be possible to better understand how interactions between households and their environment lead to the emergence of food security outcomes. The formation of typologies provides one way to classify households based upon livelihoods. By grouping together similar types of households and developing profiles of these groups it is possible to take within-community variation into account (Emtage *et al*., 2007). Attempts to create landholder typologies are documented throughout the literature (Emtage, 2004; Van Herzele and Van Gossum, 2008). A number of household typologies have also been constructed for Malawi. Here quantitative techniques such as clustering have been favoured (Kydd, 1982; Dorward, 2006; Orr and Jere, 1999).

Differences between the resulting typologies reflect contrasting objectives arising from the intended application of the classifications. The number of household 'types' identified is sensitive to the initial selection of cluster variables. Although previous studies have constructed typologies to investigate pest management strategies (Orr and Jere, 1999) and household behaviour and welfare (Dorward, 2002), an extensive review of the literature failed to uncover a typology corresponding to the livelihoods and food security status of rural households within Southern Malawi.

Burchi and Munro (2016) acknowledge that the SLF has been more widely used among development organisations than it has in academic contexts. Since 1995, the promotion of sustainable livelihoods has comprised part of the United Nations Development Programme's overall Sustainable Human Development mandate (UNDP, 1990). In order to direct programme design, monitoring, and evaluation, the NGO CARE, has also embraced Household Livelihood Security, a variation on the SLF (CARE, 2002).

More recently, application of the SLF to the study of coastal areas and fisheries development has demonstrated the potential of the framework in research settings (Allison and Horemans, 2006; Ahmed *et al*., 2010; Ferrol-Schulte *et al*., 2013). Within the context of coastal areas, application of the framework has been praised by Ferrol-Schulte *et al*., (2013) for its ability to answer not just how many people are poor, but why. Components of the framework have also been used to investigate the link between livelihoods and rural poverty reduction in Malawi (Ellis *et al*., 2003), Tanzania (Ellis and Mdoe, 2003) and Uganda (Ellis and Bahiigwa, 2003). Throughout the second chapter of this thesis attempts will be made to operationalise the SLF and ask – not just how many people are food insecure, but why?

1.5.8.2 Developing an Empirical ABM of Household Food Security

Previous sections of this introductory chapter have demonstrated how an ABM of household food security might prove beneficial when addressing the complexity of household food security (see Section 1.5.3). As a relatively new technique, there are a small number of examples whereby agent-based modelling has been used to evaluate food security. A systematic review of the literature by Van Wijk *et al*. (2014) uncovered a total of 14 ABMs.

Consideration of these existing ABMs has enabled a number of research gaps to be uncovered. Models identified by Van Wijk *et al*. (2014) were selected for their focus upon food security, however few provided detailed assessments of the phenomenon. The majority of ABMs were found to focus upon the production of food by households (Van Wijk *et al*., 2014). This emphasises food availability, but fails to encapsulate access, utilisation and stability dimensions of food security sufficiently.

In all cases except two (see Matthews and Pilbeam, 2005; Schreinemachers and Berger, 2011), decision-making took place on a seasonal or yearly basis. As a result, the dynamic, path dependent nature of household food security was frequently simplified. A number of studies have highlighted the importance of seasonality in shaping food security within rural contexts (Agarwal, 1990; Leonard, 1991; Babu *et al*., 1993; Ndekha et al., 2000; Dostie *et al*., 2002). Regarding food consumption patterns for example, substantial intra-annual fluctuations in anthropometric measurements of both children and adults have been documented (Leonard, 1991; Maleta *et al*., 2003). Despite early investigations into the link between seasonality and food security, Hirvonen *et al*. (2015) argue the dynamic nature of food security has been overlooked in both research and policy arenas recently.

Interestingly, most models included within the review implemented rule-based decision-making (Van Wijk *et al*., 2014). This demonstrates the capacity of agent-based simulations to represent heuristics effectively. Two models however used optimisation under linear programming (see Schreinemachers and Berger, 2011; Shively and Coxhead, 2004). This provided a normative evaluation of the productive strategies of farmers. In both cases farmers made optimal decisions, maximising profits whilst minimising risk (Schreinemachers and Berger, 2011; Shively and Coxhead, 2004). Such normative approaches highlight optimal outcomes given constraints. However, they tend not to reflect real-world decision processes and therefore offer little guidance regarding the practical achievement of ideal outcomes (Verburg *et al*., 2015).

A handful of models investigated by Van Wijk *et al*. (2014) used existing protocols such as the Overview, Design concepts and Details (ODD) protocol to document model procedures (Bert *et al*., 2011; Brady *et al*., 2012). The ODD was developed by Grimm (2006) in response to criticisms surrounding the irreproducibility of ABMs. It provides a standardised structure with which to outline key elements of ABMs. Validation of models was typically overlooked by the authors of simulations included within the review. Schreinemachers and Berger (2011) did however, deal with both model validation and uncertainty.

Validation of ABMs is a crucial stage of the model development process that acts to enhance credibility (Dearing *et al*., 2012). Moss (2008) acknowledges that the inherently complex nature of ABMs poses a significant challenge to validation efforts. A recent review by Bert *et al*., (2014) identified two distinct, but complementary approaches to model validation. These comprise firstly, validation of model components and processes and secondly, empirical validation (Bert *et al*., 2014). For the former, face validation is employed to ensure that model mechanisms and properties correspond to those of the real world (Rand and Rust, 2011). While for the latter, simulation outputs are validated against empirical data representing one or more stylized facts (Bert *et al*., 2014). Refsgarrd *et al*. (2005) argue that model credibility can be further promoted by taking an iterative approach to model construction, with peer reviews at various stages of model development. Within this context two types of experts can be recognised: i) the model builders themselves and ii) independent experts who review model assumptions and results (Macal and North, 2010). Feedback from both kinds of experts can contribute to model validation (Macal and North, 2010).

According to Jakeman *et al*. (2006) model uncertainty arises from a number of sources. Incomplete understanding of the system of interest may lead to confusion concerning which components interact and what processes to include (Jakeman *et al*., 2006). Additional uncertainties may arise from imprecise and often scarce data and measurements, which in turn may lead to uncertainty in the baseline inputs and conditions for model runs (Jakeman *et al*., 2006). Techniques such as sensitivity analysis can be used to explore model uncertainty and further enhance credibility (Alden *et al*., 2013).

In summary, there is a need for an ABM, which evaluates the multidimensional nature of food security effectively, providing separate estimates of food availability, access, utilisation and stability. An ABM with a daily or monthly time-step (rather than seasonal or yearly) could also provide better insight regarding the seasonality of food security. To be credible, the model must be constructed using an iterative approach and validated against existing data. In addition, uncertainty must be taken into account. Chapter three of this thesis describes the development of an agent-based model founded upon these guiding principles.

1.5.8.3 Identifying Robust Pathways to Zero Hunger

Frequently models have been used to make predictions. For example, to predict species distribution (Coro *et al.*, 2015), the spread of disease (Bengtsson *et al*., 2015) and the outbreak of riots (Hegre *et al*., 2010).

Predictive models assume that knowledge regarding the system of interest can be consolidated into a single model (Bankes, 1993). This can then be used as a replica of the real-world system and employed in a predictive manner. In some cases, such consolidative models can be used to great effect (Orrell, 2008). This is particularly true when the system of interest is equal to the sum of its parts (Mazzocchi, 2008). However, complex systems are defined by the fact that they are far greater than the sum of their parts (Mazzocchi, 2008). Interactions between components can lead to the emergence of non-intuitive and sometimes surprising behaviour (Meadows, 2008). In Section 1.5.5 it was argued that such consolidative use of complex models has led to criticism. Dearing *et al*. (2012, p.768) further argue that models of social-ecological systems lacking key feedbacks "*should not be used to predict causality"*.

By acknowledging that models of complex systems are characterised by uncertainty, an alternative approach to the application of such simulation tools was borne. A relatively novel approach, EMA provides a strategic method to explore a wide-range of plausible futures (Agusdinata, 2008). The theoretical underpinnings of the approach are widely documented (Bankes, 1993; Lempert *et al*., 2003; Agusdinata, 2008). However, there are few empirical examples of where the technique has been applied (Kwakkel and Pruyt, 2013). Typically, EMA has been combined with systems dynamics (Kwakkel and Pruyt, 2015). A variety of complex problems have been investigated using systems dynamics, including: salt water intrusion in coastal aquifers (Kwakkel and Slinger, 2012), limits to global water use (Kwakkel, 2012), scarcity of minerals (Pruyt, 2010) and the influenza pandemic (Pruyt and Hamarat, 2010).

There are only a few published examples of the combined use of EMA and agent-based modelling. These have explored the energy transition (Hamarat and Pruyt, 2011) and societal responses to climate change (Greeven, 2015). As a result of the small number of applications there is limited discussion regarding which tools to use to implement EMA within ABMs. Chapter four of this thesis attempts to add to this discussion by describing an approach using a number of accessible toolkits within the R statistical programme (https://www.r-project.org/). This body of work represents one of the first applications of EMA to better understand the dynamics of household food security and navigate pathways towards zero hunger.

Chapter 2: Unpacking Diversity: Typology Creation and Livelihoods Analysis to Support Food Security Policy in Rural Southern Malawi

Abstract

In order to address household food security within developing country contexts, there is a need to unpack and understand the wide diversity amongst smallholder farms. By identifying household types based upon shared attributes and livelihood strategies, the design and targeting of policy instruments and extension programmes may be improved. This study describes the process of constructing a typology of rural households in Southern Malawi. A cluster analysis using Integrated Household Survey data on land, labour, livestock assets and gender, identified three distinct household types: farmers, agricultural labourers and non-agricultural workers. Application of the Sustainable Livelihoods Framework enabled greater understanding of the way in which households use their assets to form livelihood strategies. Non-agricultural workers were found to have the strongest capital endowment, except for natural capital. Farmers were characterised by limited social capital, whilst agricultural labourers had the weakest asset endowment overall. For all three groups approximately 80% of household expenditure was associated with food. However, the groups differed in their food security outcomes, with 68.6% of agricultural labourers being food-energy deficient, compared with 64.7% of farmer households and 59.3% of non-agricultural worker households. Agricultural labourers were the most at risk of micronutrient deficiencies (Vitamin A, iron and zinc), followed by farmers and non-agricultural labourers. We highlight the need to agree standard food security indicators, methodologies and cut-off points for an effective typology approach. Finally we use the typology to identify potential pathways to alleviate food insecurity in rural Southern Malawi.

Key words: Rural livelihoods, nutrition, dietary diversity, cluster analysis

2.1 Introduction

Hunger remains a serious problem for almost 800 million people worldwide, with the prevalence being particularly high in rural Sub-Saharan Africa (FAO *et al*., 2015). In order to address household food security within developing country contexts, there is a need to unpack and understand the wide diversity amongst smallholder farms. According to the SLF (Chambers and

Conway, 1991; Scoones, 1998), a household's food security status can be considered an emergent property of the livelihood strategies it chooses to adopt. These are in turn shaped by the way in which households acquire and utilize assets, given a context of vulnerability and the underlying impact of policies, institutions and transforming processes. The framework recognises the multiple interactions between the various factors that affect livelihoods and emphasises their often complex and non-linear nature (Chambers and Conway 1991; Scoones, 1998).

The diversity in agro-ecological settings and heterogeneity amongst rural households within Southern Malawi pose a particular challenge to the alleviation of food insecurity (Ellis, 1998; Ellis and Freeman, 2004; Dorward, 2006). Rather than a 'one-size fits all' strategy, a far more targeted approach for policy instruments and extension programmes is required to promote ideal food security outcomes. The formation of a household typology may be of great use within this context. By grouping together similar types of households and developing profiles of these groups it is possible to take within-community variation into account (Emtage *et al*., 2007). Understanding the needs of these groups is important as they may comprise households who are varyingly in the stages of 'hanging-in', 'stepping-up' and 'stepping-out', with policies designed to help one group running the risk of increasing vulnerability in others (Dorward *et al*., 2009).

Kydd (1982), Dorward (2006) and Orr and Jere (1999) describe early attempts to classify rural households within Malawi using cluster-based approaches. Dorward (2002) has also outlined a methodology to distinguish farm households using clustering, based upon resource and environmental variables. The purpose of the analysis was to first categorise rural Malawian households into a limited number of types, before developing models describing the impact of endogenous and exogenous factors upon household wellbeing (Dorward, 2002). Using data from the 1998 Integrated Household Survey, farm households were clustered based on a number of variables associated with personal endowments such as land area, gender, education and income (Dorward, 2002). The resulting clusters were then described based upon anticipated livelihood strategies of households with labels including, 'larger farmers', 'employed', and 'borrowers' (Dorward, 2002).

Jansen et al. (2006) took a slightly different approach. Instead of using a suite of variables associated with household wellbeing, they focused upon two key assets: land and labour. A total of seven livelihood strategies were identified for households in the hillside areas of Honduras, including: 'livestock producers', 'coffee producers' and 'basic grains farmers' (Jansen *et al*., 2006). Determinants of each livelihood strategy were then explained using a multinomial logit model, taking into account additional biophysical and socioeconomic variables. These included farm size, age of household head, years of schooling and market access (Jansen *et al*., 2006).

Once formed, the level of food security achieved by each of the household types can be measured. Choice of a suitable food security metric however, is a difficult task. Not only do a vast number of indicators exist; recent studies have uncovered inconsistencies between the outcomes of different food security measures. Smith *et al*. (2006) for example, found the ranking of twelve countries located within Sub-Saharan Africa varied significantly when employing either availability or income-based metrics such as food balance sheets and household expenditure surveys, respectively. Comparison of seven food security indicators led Maxwell *et al*. (2014) to conclude that differences in prevalence measures are the result of variations in scope, sensitivity and choice of cut-off points. As a consequence, multiple indicators should be employed in the measurement of food security, with attention given to the aspects of food security each measure embodies (Maxwell *et al*., 2014). It is in this context that applying an analytical framework, such as the SLF (Chambers and Conway, 1991; Scoones, 1998) may be helpful.

This study has two main objectives: firstly, to construct a typology of rural households within Southern Malawi and secondly, to apply the SLF to describe the asset endowments and food security outcomes for each group. These then enable us to tackle a third objective: to consider how the typology may facilitate greater understanding of household food security and support targeting efforts. The chapter begins with a description of the methods, whilst section 2.3 provides the results of typology creation and subsequent sustainable livelihoods analysis. The potential of the framework to direct food security policy and extension programmes is discussed in the final section, using rural Southern Malawi as a case study.

2.2 Methodology

2.2.1 Study Area

The study area is rural Southern Malawi, where the vast majority of households are engaged in rain-fed agriculture. The principal crop of the smallholder sector and the staple diet of the population is maize (NSO, 2012a). A single growing season exists between the months of November and March. This is followed by a dry season from April to October (Orr *et al*., 2009). Smallholders with access to *dimba* fields located in the valley bottoms may extend maize cultivation beyond the end of the rains by taking advantage of residual moisture (Orr *et al*., 2009). However, the predominance of rain-fed agriculture leaves farmers vulnerable to climatic variability, climatic shocks and food insecurity (Sahley *et al*., 2005). Safety net programmes for smallholders have followed two main paths: i) the provision of input subsidies and ii) variants on food-for-work or cash-for-work schemes (Harrigan, 2008).

2.2.2 Data

Data for this study came from the Third Integrated Household Survey (IHS3) (NSO, 2012a). The National Statistical Office of Malawi conducted the survey from March 2010 to March 2011. The main objective of the IHS3 was to provide and update information surrounding the welfare and socio-economic status of Malawian households. Four questionnaire instruments were employed including household, agriculture, fishery and community questionnaires. The survey selected households based on a two-stage stratified sampling process and a Probability Proportional to Size design. As a result the sample was representative at national as well as district levels. A total of 12271 households were sampled, made up of a cross-sectional sample set (74%) and a smaller, panel sample set (26%). Cross-sectional households were visited once in 2010/11, whereas panel households were visited twice: once in 2010/11 and again in 2013. For this study, cross-sectional households from rural areas of southern Malawi were extracted to give a sample of 3840 households.

2.2.3 Typology Formation

The sampled IHS3 data set (n = 3840) was divided into a training set (75%) and a validation set (25%) before continuing with the cluster analysis. Construction of household typologies followed a similar process to that of Jansen *et al*. (2006), with four distinct stages undertaken: i) selection of variables; ii) principal components analysis; iii) hierarchical clustering on principal components and iv) validation.

2.2.3.1 Selection of Variables

An extensive review of the literature was used as a basis to identify suitable variables for typology creation. This led to the selection of 7 variables associated with four key attributes of households, which center upon land, labour, livestock and gender. Studies have shown that variables associated with two household assets: land and labour, are useful when attempting to cluster households based upon livelihood activities (Jansen *et al*., 2006). As a result the proportion of time spent by family members on agricultural and non-agricultural activities, as well as the proportion of land under cultivation were included as variables for the typology analysis.

In addition, the number of livestock and poultry owned by a household were taken into account, along with the gender of the household head. These variables were found to be important during earlier efforts to construct a typology of rural households within Malawi (Orr and Jere, 1999; Dorward, 2002).

To allow comparison with other livelihoods-based typologies such as Jansen *et al*. (2006), attempts were also made to incorporate the proportion of land used for different annual and permanent crop types, in addition to the time spent tending to livestock and fishing. However, these variables were later neglected for reasons of data scarcity.

2.2.3.2 Principal Components Analysis

Principal components analysis (PCA) was used as a pre-processing step. The aim of the analysis was to reduce the dimensionality of the dataset whilst retaining as much variation as possible. This would enable a more stable hierarchical tree to be produced through subsequent clustering.

2.2.3.3 Hierarchical Clustering on Principal Components

Using components identified through the PCA, in addition to Euclidean distance and ward agglomeration criteria, households were assembled into a hierarchical tree (Husson *et al*., 2010). Agglomerative hierarchical clustering is a 'bottom up' approach. The method creates a hierarchy from individual observations by progressively merging clusters (Husson *et al*., 2010). The Euclidean distance was used to decide whether to merge observations into clusters or not (Lê et al. 2008). In order to further aggregate sets of clusters, a linkage criterion, termed Wards agglomeration was used (Lê et al. 2008). The linkage criterion was used to determine the distance between sets of observations as a function of the pair-wise distances between observations (Lê et al. 2008). Wards agglomeration criterion selected pairs of clusters to merge at each step based on the decrease in variance for the cluster being merged (Husson *et al*., 2010). The hierarchical nature of the approach meant clusters were linked by short branches if they exhibited high levels of similarity, and by longer branches as their similarity decreased. The shape of the resulting hierarchical tree was used as a guide to select the number of clusters for k-means clustering (Lê et al. 2008). This was used to partition the tree and define individual clusters. The whole procedure of typology formation was performed using the FactoMineR package (Lê et al. 2008) in R (http://www.r-project.org/).

2.2.3.4 Validation

Three different approaches were used to validate the typology. Firstly, a one-way anova was conducted to test the stability of the clusters. In order to investigate the effect of the number of variables on stability of clusters, typology formation was also repeated, dropping one of the variables each time. Secondly, the process of typology formation was conducted with the validation set. Thirdly, data from a separate panel sample collected in 2010/11 was used to explore the seasonality of clusters. The typology analysis was repeated twice more, including data collected between the months of March and September (n = 955) and April only (n = 291).

2.2.4 Applying the Sustainable Livelihoods Framework

Having constructed a typology of households within rural Malawi, the SLF was operationalized to explore the food security status of different household types. Data from IHS3 was supplemented with relevant literature to explore the vulnerability context, livelihood assets, policies, institutions and processes and food security outcomes associated with each of the household types.

2.2.4.1 Vulnerability Context

Trends, shocks and seasonal shifts encompass the vulnerability context. As the IHS3 data set covers 2010/11 only, longer-term trends in population growth and land degradation could not be investigated. The impact of shocks and seasonal shifts on the other hand could be understood at the household level using data from IHS3 modules on shocks and coping strategies and food security.

2.2.4.2 Livelihood Assets

According to the SLF, five forms of capital constitute a household's livelihood assets (Chambers and Conway, 1991; Scoones, 1998). These include: human, social, natural, physical and financial capital. Variables corresponding to each of the five capitals were drawn from the IHS3 data set. In the case of physical capital, two different Asset Wealth indices were created, one relying entirely on livestock assets (Nyirenda *et al*., 2000) and one also taking into account durable goods such as radios and bikes (Binauli *et al*., 2000). One-way anova and Tukeys HSD were used to compare results across the different household types. Significant variables were then selected to construct an assets pentagon. This allowed comparisons between the capital endowments of different household types to be made.

2.2.4.3 Policies, Institutions and Processes

At the household level, data on access to input subsidy programmes, land tenure and extension services, was drawn from the IHS3 to understand the effect of policies, institutions and transforming processes, respectively.

2.2.4.4 Food Security Outcomes

Three classes of food security and nutrition indicators were analysed: i) household expenditure indicators as a proxy for economic vulnerability; ii) food consumption indicators, which provide information on diet quantity; and iii) calorie and micronutrient consumption levels and dietary diversity indicators, which highlight diet quality. Each of the indicators could be related to a particular dimension of food security, namely food availability, access and utilization (Table 2.1). Following recommendations by Maxwell *et al.*, (2014), multiple indicators were chosen to represent each dimension of food security. Each measure was selected to represent a different aspect of the dimension it embodied to give a comprehensive assessment of food security outcomes within rural Southern Malawi. Taking food utilisation as an example, household food variety and diversity estimates provide an idea of diet quality and the dependence of households upon staple foods. Calorie and micronutrient consumption levels on the other hand capture the nutritional composition of household diets. In addition, micronutrient deficiencies provide an assessment of the nutritional adequacy of diets relative to thresholds of minimum nutritional requirements for a healthy life.

Table 2.1: Indicators to measure food security outcomes in terms of economic vulnerability, diet quantity and diet quality.

Indicator Class	Indicator [unit of measurement]	Dimension
Economic Vulnerability	Percentage of expenditures on food [%]	Access
	Food expenditure per capita [MK/day]	
	Total expenditure per capita [MK/day]	
Diet Quantity	Daily food energy consumption per capita [kcal/day]	Availability
	Extent of inadequate calorie intakes [%]	
Diet Quality	Household Food Variety Score (HFVS) [food items/week]	Utilisation
	Household Dietary Diversity Score (HDDS) [food groups/week]	
	Percentage of household food energy from staples [%]	
	Iron consumption per capita [mg/day]	
	Zinc consumption per capita [mg/day]	
	Vitamin A consumption per capita [RAE µg/day]	

Micronutrient adequacy [%]
Extent of inadequate micronutrient intakes [%]

Diet quality and quantity indicators are derived from the IHS3 consumption module while economic vulnerability indicators are supplemented with data from expenditure modules. The consumption module documents household food expenditures and consumption over seven days prior to the interview. The majority of food quantities are reported in local units such as pails, plates or bunches. Food quantities are disaggregated by source, i.e. purchased foods, own-production and food received in-kind. Expenditures are reported for purchased foods only.

In order to calculate the calorie and nutrient content of household diets, food quantities were first converted into standard units (kg) using conversion factors by Verduzco-Gallo *et al*. (2014). Quantities were then adjusted to subtract non-edible portions. This was achieved by multiplying the weight of each food type by its corresponding edible portion coefficient (Appendix A). Food composition tables were then used to calculate the calorie and nutrient content (iron, zinc, and Vitamin A) of different foods (Appendix A). As there are no recent food composition tables for Malawi, we were obliged to draw on data from West Africa (Stadlmayr *et al*., 2012) and Mozambique (Korkalo *et al*., 2011).

Total daily intakes of energy, vitamin A, iron and zinc were summed for each household and allocated to household members. As intra-household allocation of food is not documented by the IHS3, adult male equivalent (AMEs) units were used as a proxy. AME units were calculated according to FAO estimates of individual energy requirements that vary according to age and gender (Smith and Subandoro, 2007). The energy requirement of a 19 to 30 year old male was used as a reference value (3000 kcal/day, AME = 1) with other age and gender groups weighted accordingly (Smith and Subandoro, 2007). AME units were used based on the assumption that the FAO energy requirements are true for the population of interest and that household food intakes were allocated to individuals in proportion to energy requirements. In agreement with Bermudez *et al*. (2012), households with implausible calorie consumption levels were removed from the sample. This included households with less than 500 and greater than 6000 kcal per household member per day. Such households comprised 17.5% of the original sample, bringing the total number of observations to 2267 households and 9767 individuals.

Apparent individual intakes of energy and micronutrients were compared with established requirements. To evaluate the adequacy of dietary energy intakes, individual calorie consumption levels were related back to the age and gender specific requirement levels outlined in Smith and

Subandoro (2007). For vitamin A, apparent intakes were assessed against the Estimated Average Requirements (EARs) outlined by the Institute of Medicine (IOM, 2001). For iron, the EARs have been defined by IOM (2001) based upon bioavailability factors for a 'typical American diet'. In order to make the EARs more representative of Malawian diets, which are lower in animal sources of iron, an assumption of 5% bioavailability was taken (Verduzco-Gallo *et al*., 2014). Values obtained from IOM (2001) were adjusted from 10% bioavailability for children and 18% bioavailability for adults, to 5% iron bioavailability for both children and adults *(Verduzco-Gallo et al*., 2014). For zinc, comparisons were made between apparent intakes and physiological requirements for an unrefined cereal-based diet as published by Brown *et al*. (2004).

In order to assess the adequacy of intakes of vitamin A and Zinc, the cutpoint method was employed (IOM, 2001). Household members with intakes below the recommendations for their age and gender were classified as having inadequate intakes of that micronutrient. Unlike vitamin A and zinc, iron requirements are not normally distributed for young children and women of reproductive age. As a result, the full probability approach was required to evaluate the adequacy of iron intakes (IOM, 2001). Household members were assigned a probability of inadequacy based upon the range their iron intakes fell into (IOM, 2001). The percentage of inadequate intakes could then be determined by summing the probabilities.

The diversity of household diets was explored using two indicators. The Household Food Variety Score (HFVS) counts the number of different food items that the household consumed during the seven-day recall period. The Household Dietary Diversity Score (HDDS) counts the number of different food groups consumed over the seven-day recall period. The HDDS considers 12 food groups: cereals; roots and tubers; pulses/ legumes and nuts; vegetables; fruits; meat (including offal) and poultry; fish and seafood; eggs; milk and dairy products; oils and fats; sugar, honey and sweets; and miscellaneous including condiments (Swindale and Bilnsky, 2005; Swindale and Bilinsky, 2006). An additional indicator, the percentage of household food energy from staples is calculated as the proportion of calories from cereals and roots and tubers.

2.3 Results

2.3.1 Typology Formation

The principal components analysis applied a linear transformation to the variables, resulting in the first 4 dimensions being considered within the hierarchical clustering on principal components and retaining 78.1% of the variation (Fig. 2.1). The subsequent hierarchical analysis distinguished 3 clusters (Fig. 2.2). A total of 2479 households within the training set possessed complete cases and so were included within the analysis. One-way anova and Tukeys HSD revealed significant differences between each of the clusters for at least one of the variables. Table 2.2 provides a summary of the means and standard errors for the variables that were used in the analysis. Significant results from two-tailed t-tests for each variable between every cluster combination are also documented. Dropping variables from the typology analysis was found to lead to four, less stable clusters.

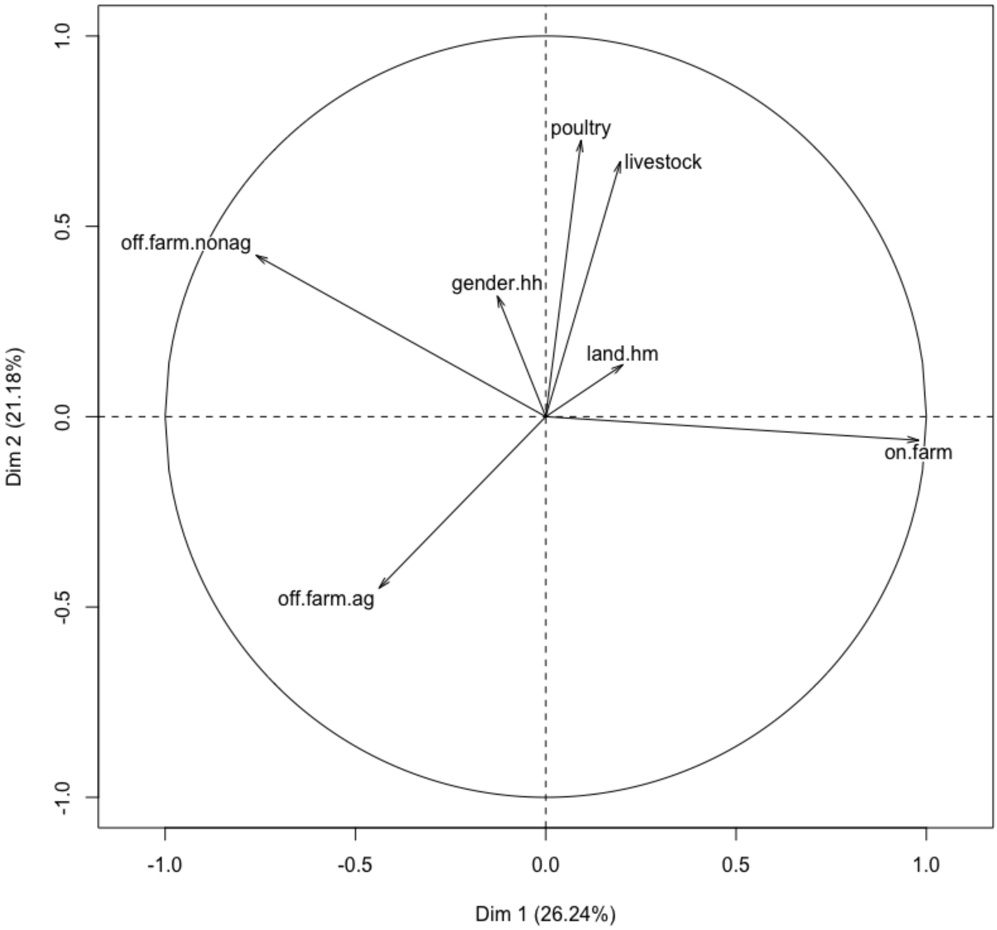

Figure 2.1: Factor map corresponding to the principal components analysis. See Table 2.2 for variable descriptions.

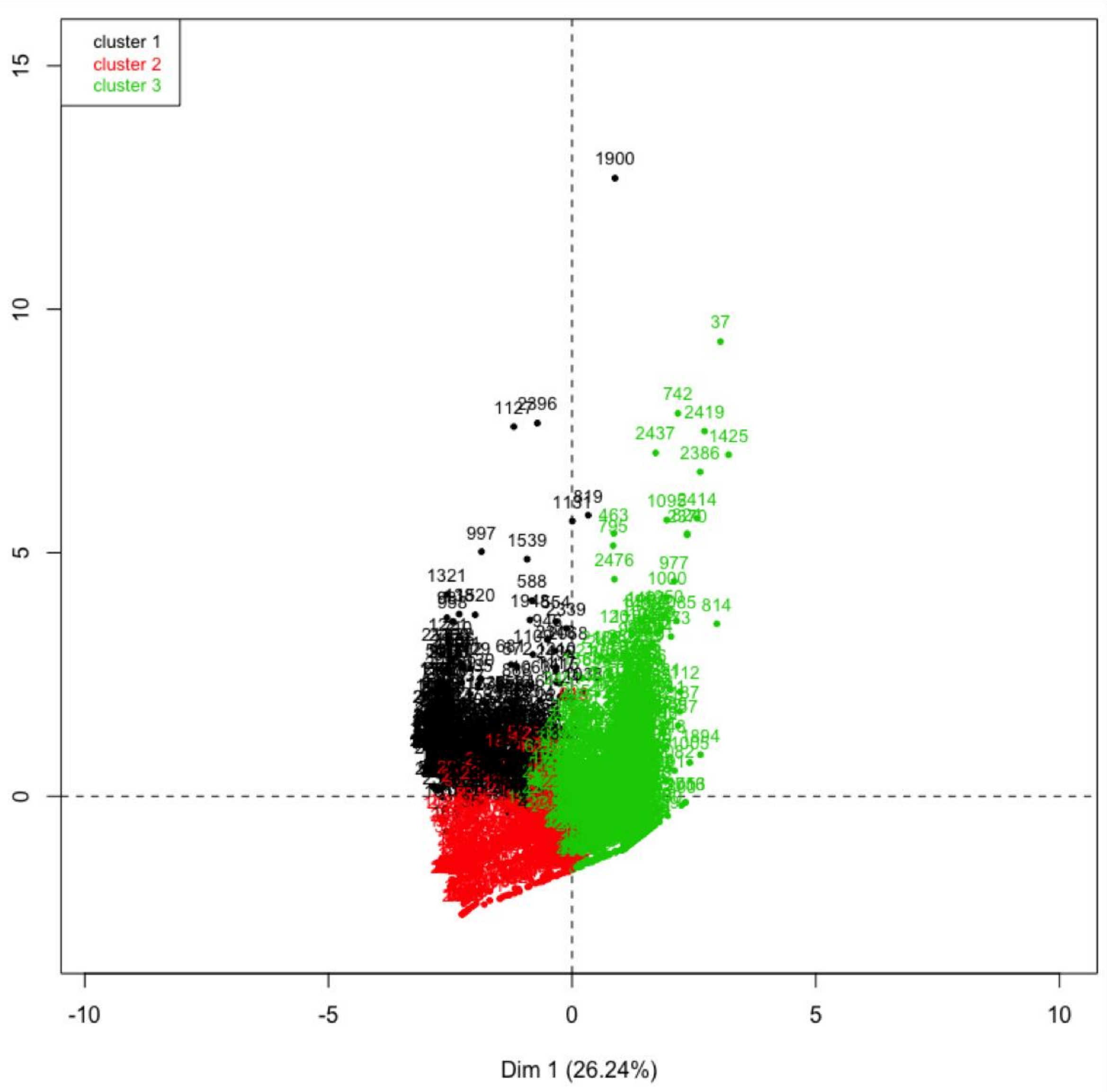

Figure 2.2: Factor map of resulting clusters

A repeat of the cluster analysis with the validation set provided further evidence for the stability of clusters (S1: Table 2.5). The impact of seasonality upon clustering was also found to be negligible. Analysis of data collected between the months of March and September (n = 955) resulted in 3 clusters corresponding to those identified in the original data set (n = 2479). Analysis of data collected in April only (n = 291) revealed 4 clusters, 3 of which matched the original data set. The fourth cluster comprised of just two households with unusually high numbers of livestock.

Table 2.2: Final clusters and summary statistics of variables.

	Full Sample		Cluster 1 Farmers		Cluster 2 Agricultural labourers		Cluster 3 Non-agricultural workers	
n	2479		1588		397		494	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Family Labour (activity time/ total family labour)								
On-farm work	0.70	0.007	$0.94^{(2, 3)}$	0.003	$0.34^{(1, 3)}$	0.012	$0.21^{(1,2)}$	0.009
Off-farm agricultural work	0.13	0.005	$0.04^{(2, 3)}$	0.002	$0.63^{(1, 3)}$	0.012	$0.02^{(1, 2)}$	0.003
Non-agricultural work	0.18	0.006	$0.03^{(3)}$	0.002	$0.03^{(3)}$	0.005	$0.77^{(1, 2)}$	0.009
Cultivated Land (ha/household member)								
Land area	0.18	0.004	$0.19^{(2, 3)}$	0.005	$0.14^{(1)}$	0.006	$0.17^{(1)}$	0.008
Livestock Assets (number of livestock owned per household)								
Livestock	1.18	0.060	$1.38^{(2)}$	0.082	$0.46^{(1, 3)}$	0.072	$1.13^{(2)}$	0.129
Poultry	2.95	0.115	$3.04^{(2, 3)}$	0.143	$1.38^{(1, 3)}$	0.157	$3.93^{(1,2)}$	0.316
Gender (proportion of female headed households,%)								
Proportion of female headed households	26.4		$28.5^{(3)}$		$28.0^{(3)}$		$18.4^{(1,2)}$	

$^{(x)}$ = statistically significant difference between column cluster and cluster no. x at 5% level.

2.3.1.1 Description of Household Types

Differences between the utilisation of land and labour resources by each cluster were used to provide a label and description relating to the livelihood strategy of each distinct type (Table 2.2).

Cluster 1 households for instance, are termed *farmers* and make up the majority (64%) of the sample (n = 2479). A large proportion of time (94%) is allocated to subsistence farming by these households. In addition, *farmers* tend to own greater numbers of livestock and poultry, with a mean of 1.38 and 3.04 compared with 1.18 and 2.95 for the whole population, respectively.

Cluster 2 households on the other hand, comprise 16% of the overall sample (n = 2479) and in contrast with *farmers* (cluster 1) only 34% of labour is allocated to on-farm agricultural work. Instead, the vast majority of family labour is given to agricultural work on other people's farms, termed *ganyu* (63%). The area of land cultivated is also significantly smaller for cluster 2 households compared with *farmers*. It is for this reason that cluster 2 households are regarded as *agricultural labourers*.

Finally, cluster 3 households (20% of the sample) are distinguished primarily by the amount of labour allocated to non-agricultural work. Almost 80% of labour is given to either the running of, or helping out with household non-agricultural and non-fishing businesses. As a result, households within cluster 3 are termed *non-agricultural workers*. Members of this cluster possess significantly less land per household member on average. Interestingly however, numbers of livestock and poultry are greater than average at 1.0 and 4.1, respectively. This suggests that labour allocated to on-farm work may be biased towards the care of livestock rather than the production of food crops. The proportion of female-headed households is also significantly lower for this cluster at just 18%, compared with almost 30% for cluster 1 and cluster 2.

2.3.2 Sustainable Livelihoods Analysis

2.3.2.1 Vulnerability Context

According to the sustainable livelihoods framework, in addition to long-term trends, households may face short-term shocks and seasonal shifts (Chambers and Conway, 1991; Scoones, 1998). From the IHS3 case study data set (n = 2479), over 80% of households reported having experienced at least one shock over the past year. The proportion of households experiencing shocks was highest for agricultural labourers and lowest for non-agricultural workers at 87.7% and 75.5%, respectively. The type of shocks affecting households was similar for all three clusters. Drought/ irregular rains were reported by 38.5% of households, followed by unusually high prices for food (14.9%) and unusually high costs of agricultural inputs (11.9%). Other shocks included: serious illness or accident of household member(s) (7.1%), unusually low prices for agricultural output (4.4%) and theft of money/ valuables/ assets/ agricultural output (3.1%). The impact of shocks was also comparable across all three household types. Typically households reported a decrease in income (79.2%), food production (87.1%) and food stocks (86.0%). The impact of shocks upon household assets was less clear, with 55.2% of households reporting no change and 44.6% of households reporting a decrease.

Variation was found in the responses of different household types to shocks. Half of the agricultural labourers for example, received unconditional help from relatives/ friends, compared with 32.6% of farmers and 29.4% of non-agricultural workers. A large proportion of non-agricultural workers opted to do nothing (17.7%), while only 5.0% of farmers and 2.4% of agricultural labourers gave this response.

Seasonal shifts in food security are also documented within the IHS3 data set. On average, 64.0% of agricultural labourers reported that, in the seven days prior to interview, they had been worried that their household would have insufficient food. This peaked in the months of September and February at 75.0% and 74.2%, respectively (Fig. 2.3). More than half of farmers struggled to access sufficient food between November and December, this declined to less than 30% in August. Overall, non-agricultural workers were less likely to report insufficient food but, on average, 30.1% of this group still considered themselves to be without sufficient food.

Behaviours associated with seasonal food insecurity were also more pronounced for farmers and agricultural labourers when compared with non-agricultural workers. When asked to consider the past seven days, over 30% of farmers and agricultural labourers reported having relied upon less preferred or less expensive foods for 3 or more days, compared with just 13.5% of non-agricultural workers. The proportion of households limiting portion sizes for 3 or more days of the week was also high for agricultural labourers at 27.2% compared with farmers (16.9%) and non-agricultural workers (10.0%).

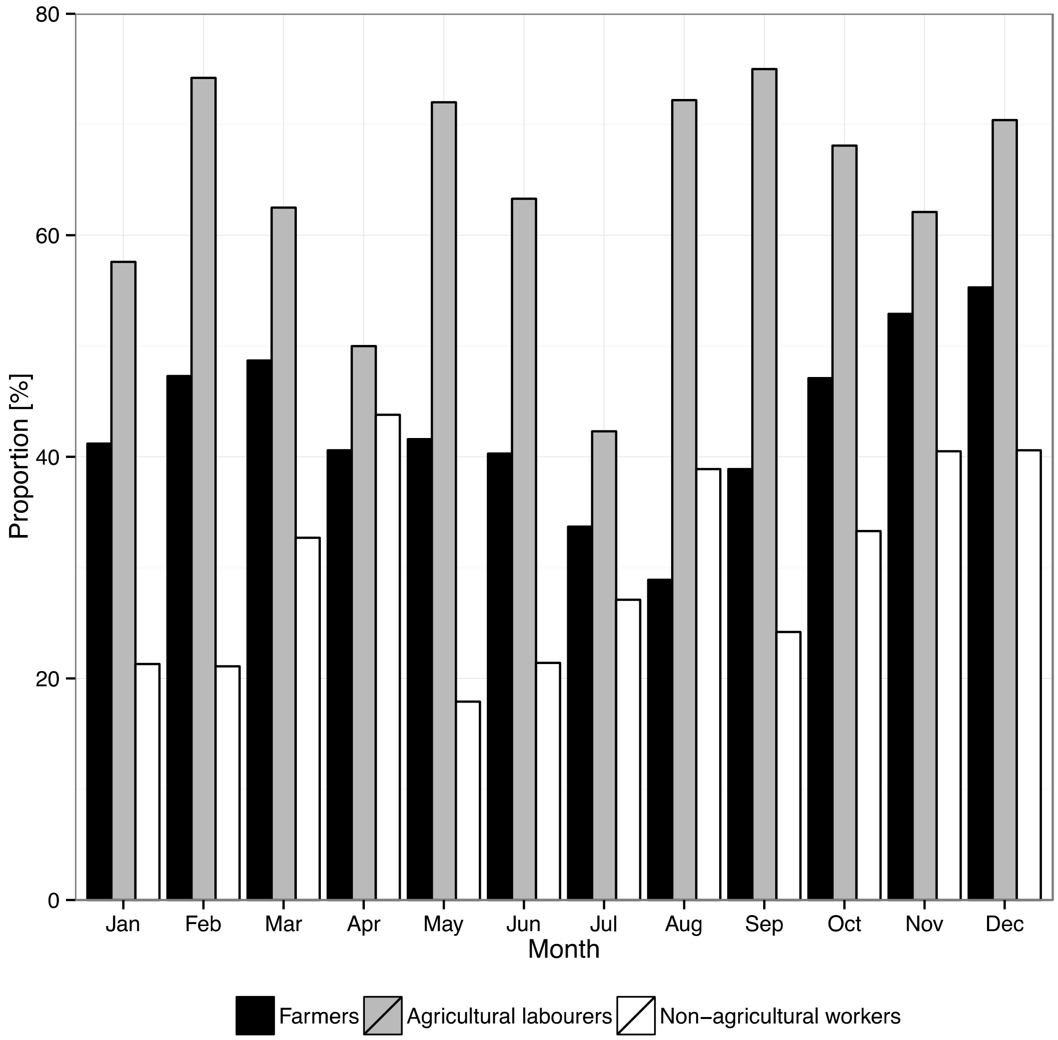

Figure 2.3: Proportion of households reporting that, in the seven days prior to interview, they had been worried that their household would have insufficient food.

2.3.2.2 Livelihoods Assets

Human, natural, financial, physical and social capitals constitute a household's asset base (Chambers and Conway, 1991; Scoones, 1998). The ability of households to acquire and manage assets has a direct effect on livelihood outcomes. Variables associated with human capital, such as household size, education level and health status were similar for all three household types (Table 2.3). Social capital, as indicated by the mean annual value for gifts received was also similar, however differences could be seen in the amount given out. Non-agricultural workers had a significantly higher value for the amount of transfers/gifts given out on averag

Table 2.3: Asset status of rural households in Southern Malawi.

Variables [unit of measurement]	**Full Sample**		**Cluster 1** **Farmers**		**Cluster 2** **Agricultural labourers**		**Cluster 3** **Non-agri. workers**	
n	2479		1588		397		494	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Human Capital								
Household size [no. of household members]	4.49	0.04	4.50	0.05	4.37[3]	0.09	4.56	0.09
Proportion of heads of households who have completed primary education [%]	18.39		16.12[3]		11.59		31.17[1,2]	
Dependency ratio (n= 2361)*	1.20	0.02	1.21	0.03	1.25	0.05	1.10	0.04
Prop. of HH reporting illness in the past 2 weeks [%]	18.28	0.51	18.01	0.65	17.37	1.13	19.89	1.16
Social Capital								
Value of transfers/ gifts received in cash, food and kind [MK]	1281.15	125.34	1246.70	115.75	1364.23	558.51	1325.10	237.17
Value of transfers/ gifts **given out** in cash, food and kind [MK]	846.86	93.13	539.91[3]	63.39	330.63[3]	103.82	2248.44[1,2]	406.47
Natural Capital								
Prop. of irrigated land (rainy season) [%]	0.32	0.10	0.41	0.15	0.34	0.19	0.00	0.00
Prop. of land with good or fair soil quality (rainy season) [%]	90.40	0.57	90.02	0.73	89.70	1.48	92.22	1.18
Total area of land owned [ha]	1.59	0.03	1.69[3]	0.15	1.34[3]	0.19	1.49 [1,2]	0.06

Cont.	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Physical Capital								
Asset wealth index 1**	28.18	2.63	30.76(2)	3.10	10.02(1,3)	1.93	34.49(2)	8.49
Asset wealth index 2***	11.25	0.20	11.63(2,3)	0.26	7.43(1,3)	0.42	13.09(1,2)	0.46
Proportion of households reporting main dwelling made out of permanent or semi-permanent materials [%]	50.63	1.00	50.38(2,3)	1.26	38.79(1,3)	2.45	60.93(1,2)	2.20
Financial Capital								
Annual crop income [MK]	5888.89	374.52	6457.11(2)	446.12	2908.48(1,3)	574.63	6457.47(2)	1117.15
Annual livestock income [MK]	1843.31	187.18	1966.32(2)	241.09	704.99(1,3)	150.25	2362.65(2)	514.74
Annual non-agricultural wage income [MK]	15212.83	1397.66	4352.12(3)	667.07	2409.23(3)	500.70	60414.95(1,2)	6271.01
Annual agricultural wage income (ganyu) [MK]	18608.07	1149.22	15988.75(2)	1148.33	31632.39(1,3)	3200.42	16561.19(2)	3567.30
Annual remittance income [MK]	488.96	50.39	605.43(2,3)	70.50	279.98(1)	72.84	282.49(1)	94.59
Credit [MK]	631.75	74.76	434.46(3)	53.44	451.39(3)	144.43	1410.93(1,2)	310.53
Total HH income [MK]	42673.81	1824.59	29804.19(3)	1402.00	38386.45(3)	3399.09	87489.69(1,2)	7140.71

(x) = statistically significant difference between cluster no. x and the column cluster at 5% level. *Ratio of children (<15 years) and aged (>64 years) to adults (15-64 years) **Score for each asset owned: 2 for chickens, 10 for goats, 100 for cattle (Nyirenda et al. 2000). ***Score for asset ownership: 2 for chickens, 7 for radio, 9 for goats, 12 for bike, 20 for cart (Binauli et al. 2000). MK = Malawi Kwacha.

Typically, farmers possessed greater amounts of natural capital when compared with other households. The total area of land owned by farming households was slightly higher at 1.69 hectares compared with 1.34 hectares for agricultural labourers and 1.49 for non-agricultural workers. In general, households regarded over 90% of their rainy season land to have good or fair soil quality. Availability of irrigated land was negligible for the whole sample.

Variation was seen between the physical capital endowments of different household types. Over 60% of non-agricultural workers reported a main dwelling made out of permanent or semi-permanent materials. This was much lower for farmers and agricultural labourers at 50.4% and 38.8%, respectively. Non-agricultural workers scored highest for both Asset Wealth Indices 1 and 2. Agricultural workers have significantly lower Asset Wealth Indices than either of the other two groups, reflecting their much lower livestock endowments.

Income from a number of sources, including crops, livestock, non-agricultural and agricultural work, as well as remittances and credit were considered when exploring the financial capital of households (Table 2.3). The majority of income for agricultural labourers came from agricultural labour (82.4%) followed by sale of crops (7.6%) and waged employment (6.3%). Farmers on the other hand generated a greater proportion of their income from the sale of crops (21.7%), while still being highly dependent upon income from agricultural labour (53.6%). In contrast to this, almost 70% of the income of non-agricultural workers came from waged employment in addition to agricultural labour (18.9%) and sale of crops (7.4%). Typically, income from remittances and credit was low for all households. Overall, total annual household income was greatest for non-agricultural workers, with a mean value of 87490 MK (roughly US $581), followed by agricultural labourers with a mean of 38386 MK (roughly US $255) and farmers with a mean of 29804 MK (roughly US $198).

One-way anova and Tukeys HSD revealed significant differences between each of the clusters for at least one of the variables (Table 2.3). These results guided the selection of variables to construct an assets pentagon (Fig. 2.4). For each of the five capitals, a single variable was selected. These were i) human: proportion of heads of household educated to primary level (and above); ii) social: value of transfers/gifts given out in cash, food and kind; iii) natural: total area of land owned (ha); iv) physical: asset wealth index 2; and v) financial: total income (see Table 2.3). In order to construct the assets pentagon and enable comparison between farmers, agricultural labourers and non-agricultural workers, variables were normalised between 0 and 1 (Fig. 2.4).

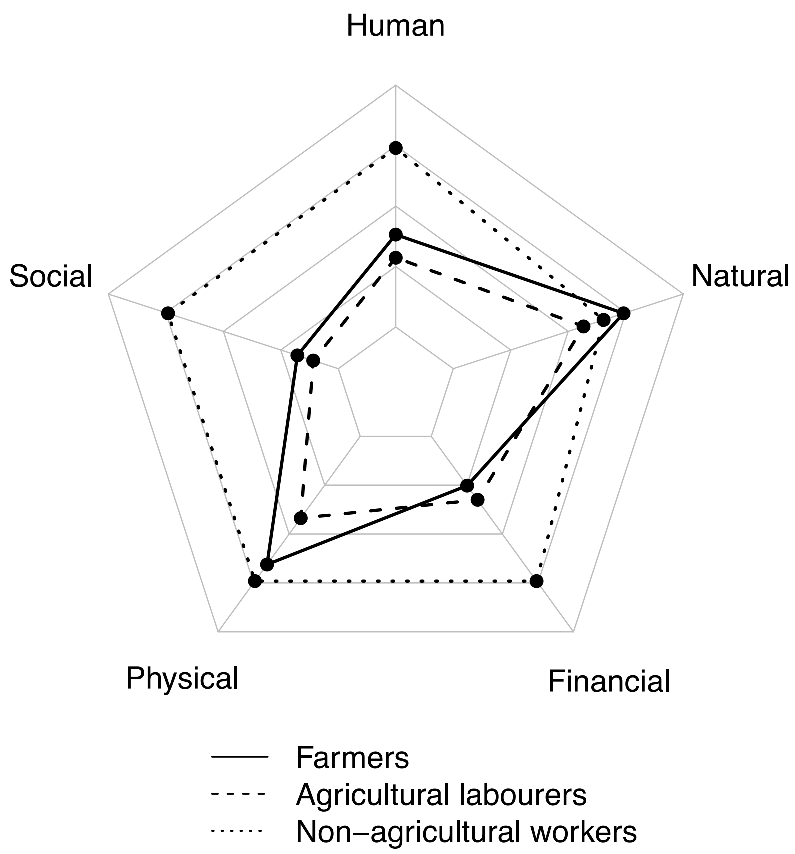

Figure 2.4: Asset pentagon for rural households within Southern Malawi. Selected variables representing human, natural, financial, physical and social capital (clockwise from top) are normalized between 0 and 1. Variable descriptions are provided in Table 4.

2.3.2.3 Policies, institutions and processes

Underlying policies, institutions and processes may have a significant impact upon how a household can employ its assets to construct a sustainable livelihood (Chambers and Conway, 1991; Scoones, 1998). Policies that affect the rate of returns to different livelihood strategies may influence the rate of asset accumulation. Input subsidies for instance, were accessed by over half of households within rural Southern Malawi. Both farmers and non-agricultural workers were more likely to access subsidised seed and fertiliser (roughly 60%), compared with agricultural labourers (41.8%).

Tenure is a critical institution in terms of determining access to land. Results from the case study data set reflect the customary nature of land tenure within Malawi. Approximately, 75.7% of households inherited land from relatives. The remaining plots were often granted by local chiefs (11.3%) or rented short-term (4.1%). Differences between farmers, agricultural labourers and non-agricultural workers were negligible.

Extension is an important transforming process, which may enable households to utilise their assets to best effect. Almost 50% of the case study data set (n = 2479) reported having received advice from extension services during the past rainy season. Interestingly, this was highest for non-agricultural workers at 50.4%, compared with farmers and agricultural labourers at 47.7% and 41.3%, respectively. In all cases, the majority of advice received by households came from the Government's Agricultural Extension Service (56.8%), followed by electronic media (21.3%), other farmers (9.8%) and NGOs (3.5%). The types of advice most frequently given by extension workers did not differ for farmers, agricultural labourers and non-agricultural workers. It included information on new seed varieties (16.2%), fertilizer use (15.4%) and composting (14.2%). In general, households regarded the advice given by extension workers to be either useful (49.3%) or very useful (47.6%).

2.3.2.4 Measuring Food Security Outcomes

Results for indicators of economic vulnerability were similar across the three household types. On average, food constituted 80% of a household's expenditure. Regarding diet quantity, average daily food energy consumption per capita was 1835.7 kcal. Approximately 68.6% of agricultural labourers were food-energy deficient, compared with 64.7% of farmer households and 59.3% of non-agricultural worker households (Table 2.4).

Variation in diet quality was also found between the different household types. Both the HFVS and the HDDS were highest for non-agricultural workers and lowest for agricultural labourers. At over 70% however, the proportion of daily energy per capita from staples was high for all household types.

Consumption of the micronutrient vitamin A was similar across all three clusters. On average daily vitamin A intake was 49.2 µg of retinol activity equivalents. Perhaps surprisingly, average iron intakes were greatest for members of farmer households at 20.8 mg per day, compared with 19.2 mg for non-agricultural workers. Overall, the apparent intake levels for iron were equivalent to 82.2% adequacy when compared with the requirements for this nutrient. The mean intake of zinc exceeded the requirements for all three household types, while the adequacy of vitamin A intakes reached less than 50% on average (Table 2.4). This was reflected in assessments of the extent of inadequate micronutrient intakes among the rural population of Malawi. Over 90% of the sample population were at risk of vitamin A deficiency, greater than half were at risk of iron deficiency and roughly a third of individuals were likely to have insufficient zinc intakes. Agricultural

Table 2.4. Results of economic vulnerability, diet quantity and diet quality indicators employed to measure food security outcomes for three different livelihood strategies.

Variables [unit of measurement]	Full Sample		Cluster 1 Farmers		Cluster 2 Agricultural labourers		Cluster 3 Non-agricultural workers	
Total no. of households	2267		1446		365		456	
Total no. of individuals	9767		6232		1518		2017	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Economic Vulnerability								
Percentage of expenditures on food [%]	82.0	0.4	81.4(2)	0.5	84.5(1)	0.8	81.7	0.8
Food expenditure per capita [MK/day]	33.3	0.7	28.8(3)	0.7	30.5(3)	1.6	49.6(1,2)	2.3
Total expenditure per capita [MK/day]	40.6	0.9	35.1(3)	0.9	35.3(3)	1.8	62.3(1,2)	3.0
Diet Quantity								
Daily food energy consumption per capita [kcal/day]	1835.7	9.9	1839.6(2)	12.5	1669.0(1,3)	22.2	1948.8(2)	22.9
Extent of inadequate calorie intakes [%]	64.2		64.7(2)		68.6(1,3)		59.3(2)	

Cont.	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Diet Quality								
Household Food Variety Score (HFVS) [food items/week]	9.9	0.1	9.6(2,3)	0.1	8.9(1,3)	0.2	11.6(1,2)	0.2
Household Dietary Diversity Score (HDDS) [food groups/week, max = 12]	6.4	0.0	6.2(2,3)	0.0	6.0(1,3)	0.1	7.2(1,2)	0.1
Percentage of household food energy from staples [%]	75.9	0.4	76.2(2,3)	0.5	80.9(1,3)	0.9	71.1(1,2)	1.0
Iron consumption per capita [mg/day]	20.3	0.1	20.8(2,3)	0.2	19.5(1)	0.3	19.2(1)	0.3
Zinc consumption per capita [mg/day]	9.5	0.1	9.7(2)	0.1	8.8(1,3)	0.1	9.7(2)	0.1
Vitamin A consumption per capita [µg RAE/day]	200.8	3.1	202.8	3.9	188.7	6.7	203.5	7.4
Iron adequacy [%][a]	82.2	0.6	84.1(3)	0.8	80.9	1.4	77.1(1)	1.3
Zinc adequacy [%][a]	152.1	1.1	153.3	1.3	146.1	2.5	152.9	2.4
Vitamin A adequacy [%][a]	49.2	0.7	49.2	0.9	48.0	1.6	50.0	1.8
Extent of inadequate iron intakes [%][b]	57.3		55.5		58.8		61.6	
Extent of inadequate zinc intakes [%][c]	35.4		35.5		36.6		34.6	
Extent of inadequate vitamin A intakes [%][c]	91.0		91.4		90.6		90.2	

(x) = statistically significant difference between cluster no. x and the column cluster at 5% level. [a]Calculated as weighted mean intake of micronutrients as a percentage of the Estimated Average Requirement (EAR) by division [b]Calculated using the full probability method (IOM 2001) [c]Calculated using the cutpoint method (IOM 2001) labourers were the most at risk of micronutrient deficiencies, followed by farmers and non-agricultural labourers.

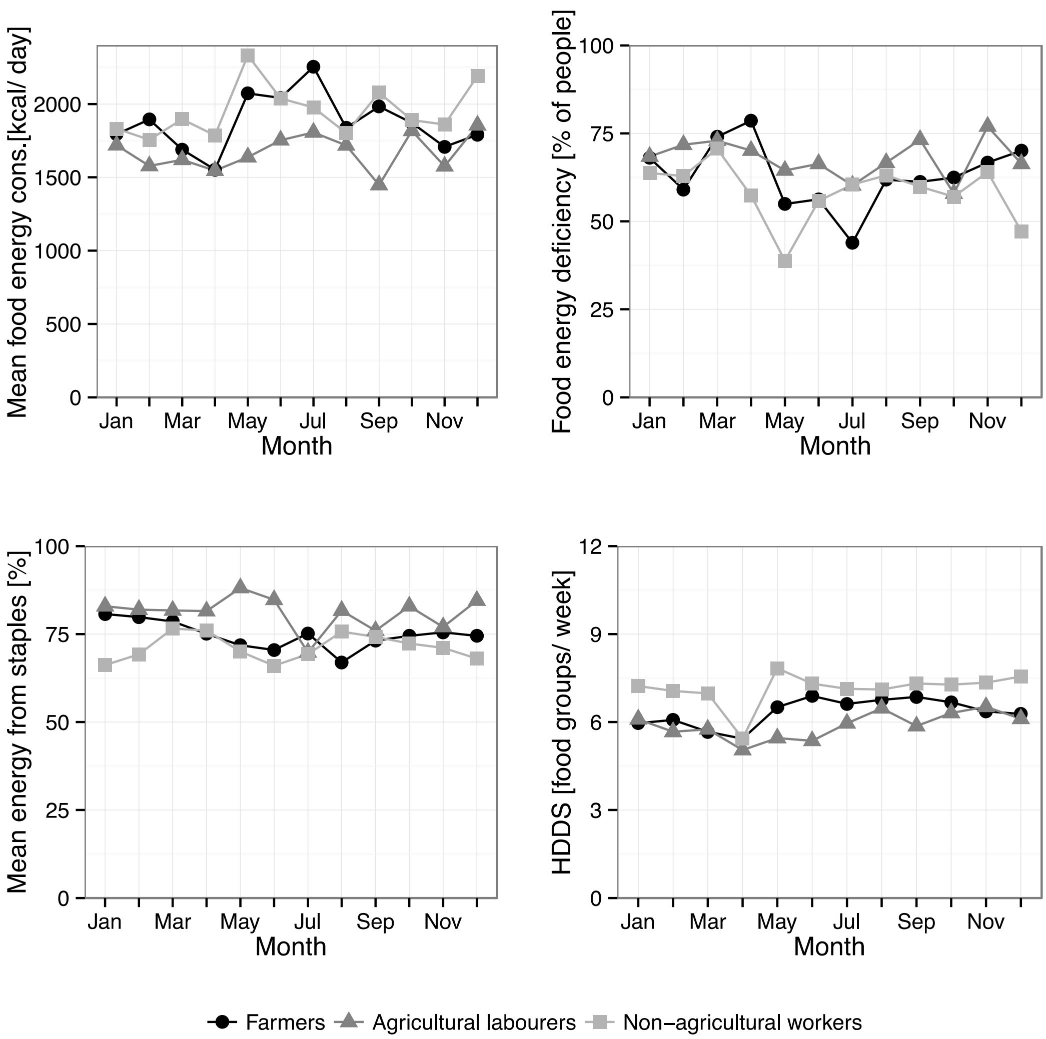

Figure 2.5: Food security outcomes throughout the calendar year. A: Mean daily food energy consumption per capita [kcal/day], B: Prevalence of food energy deficiency [% of people], C: Mean percentage of energy from staples [%], D: Household Dietary Diversity Score.

As the IHS3 data is collected over the course of the year, it is possible to explore seasonal patterns in food security outcomes (Fig. 2.5). Variation could be seen between farmers, agricultural labourers and non-agricultural workers. In the case of calorie consumption (Fig. 2.5A), the pattern is not very clear but agricultural labourers consistently consumed fewer calories per day than the other two groups though their intake was less variable across the year. In terms of the proportion of people who were food energy deficient, (Fig. 2.5B), agricultural labourers again showed consistently high levels of food insecurity with levels running at above 60% for most of the year. However, the highest levels of food energy deficiency (at almost 80%) were observed in farmers during March and April (perhaps accounted for by energy spent on bringing in the new harvest), before declining to 43.9% in July. Interestingly, the pattern of food energy deficiency for non-agricultural workers reflected that of farmers, with a more pronounced decline in food insecurity in May. There was little seasonal variation in the percentage of energy from staples (Fig. 2.5C), which remained at over 70% on average for all households throughout the course of the year. The reliance on staples was consistently higher for agricultural labourers with non-agricultural workers generally having the least dependence on staples. This was also reflected in their consistently higher dietary diversity scores (Fig 2.5D), In general, increases in mean daily food consumption per capita, were met with slightly higher dietary diversity scores. All three groups had the lowest dietary diversity in April, perhaps reflecting the availability of (and preference for) the newly harvested maize.

2.4 Discussion

2.4.1 Typology Creation

This study attempted to classify rural households based upon variables associated with land, labour, livestock assets and gender. Cluster analysis of the sampled IHS3 dataset successfully led to the identification of three household types within rural Southern Malawi, namely farmers, agricultural labourers and non-agricultural workers who differed particularly in relation to the amount of labour devoted to activities on their own farms, other's farms and non-farm activities. Repeats of the cluster analysis with a validation data set and subsamples accounting for seasonality provided evidence for the stability of the typology.

Findings are broadly consistent with previous attempts to classify households within Malawi (Dorward, 1996; Orr and Jere, 1999; Dorward, 2002). However, differences between the studies highlight the sensitivity of results to the initial selection of cluster variables. Orr and Jere (1999) for instance, classified households based upon the level of self-sufficiency in maize, the total area of land cultivated, membership of tobacco farm clubs, *dimba* cultivation habits and gender of the household head. This led to the recognition of five groups that differ in their ability to be self-sufficient in maize (Orr and Jere, 1999). Dorward (1996) on the other hand, concentrated on agricultural variables including: land area, crop allocation, fertiliser use and maize density. In this case, just two household types were identified: those who planted improved maize and those that did not. Such differences between the number of household types and their characteristics reported by each of the studies are likely to arise from contrasting aims and objectives underlying the formation of the typologies. Where the focus is on informing policies specific to maize production, there is a clear advantage in creating typologies, which include maize-related variables. Where, as in our case, the interest is in understanding food security more broadly, the use of a more general set of indicators may be justified.

Once formed, application of the SLF enabled comparisons to be made between the asset endowments of the three household types. Construction of an asset pentagon provided a clear illustration of differences in the form of human, natural, physical, financial and social capital. Non-agricultural workers were found to possess greater capacity for all capitals, except natural capital. Farmers on the other hand were characterised by limited social and financial capital, whilst agricultural labourers had the weakest asset endowment for all except financial capital.

This study highlighted the difficulty in selecting variables to represent each of the five capitals. When constructing an asset pentagon, it is hard to determine whether selected variables are good proxies or not. This is particularly true when attempting to quantify the social capital of households. Variables from the IHS3 data set, including values of transfers or gifts given out in cash, food and kind did not reflect the extent of a household's social capital in this case. When exploring the vulnerability context for example, a further variable reporting household responses to shocks found a large proportion of both farmers and agricultural labourers received unconditional help from relatives or friends.

The fact that the IHS3 dataset was conducted throughout a single year (2010/11) posed additional problems when operationalising the SLF. The long-term impact of exogenous trends such as population growth and climate change could not be elucidated using the data set. Such trends may play an important role in shaping the livelihoods of households and subsequent food security outcomes within rural Malawi. In the majority of contexts, over time households will attempt to maintain and advance their welfare (Dorward *et al*., 2009). To do this, households may expand their existing activities and/ or move into new activities. As a result household typologies may be dynamic and exhibit path dependence. Indeed, Dorward *et al*. (2009) suggest that households may opt to 'hang-in', 'step-up' or 'step-out'. In order to better understand household trajectories, future work should focus upon the construction of fixed thresholds for the classification of rural households in other years. Methods described by Falconnier *et al*. (2015) and Valbuena et al. (2014) have enabled the path dependent nature of household typologies to be explored within Southern Mali and Western Kenya, respectively. The formation of typologies can also offer an ideal starting point to model households effectively (Valbuena *et al.*, 2008).

2.4.2 Analysis of Food Security Outcomes

Our data enabled us to examine the food security outcomes of different livelihood strategies. Daily food energy consumption per capita was highest for non-agricultural workers, followed by farmers and agricultural labourers. This suggests that financial capital (which was highest for non-agricultural workers) is a particularly important factor in determining food security. The link between economic vulnerability and diet quality was also apparent. Minimal food expenditures corresponded to lower food variety and dietary diversity scores (and vice versa).

A number of assumptions were made when calculating diet quantity and quality metrics. Food consumption data in the IHS3 are reported at the household level. As a result intra-household allocation patterns are unknown. Food is therefore assumed to be distributed in proportion to the energy and nutritional requirements of each individual household member. This may be an oversimplification as studies by Katz (1995), Messer (1997) and Nanama and Frongillo (2012) imply a number of factors, in addition to gender and age, may influence resource allocation decisions. Furthermore, results from this analysis suggest that households routinely restricted consumption by adults in order for younger children to eat. Additional simplifications include the fact that food consumption recalls capture the total amount of food entering the household. Losses in the form of discarded food, animal feed and/ or servings to guests and workers are not considered; nor are contributions of food consumed away from the home.

Limitations such as these may cause observed–weighed food records or 24-h recall surveys to be regarded as the preferred consumption methodologies. However they are expensive and difficult to conduct (Fiedler *et al*., 2013). Household consumption and expenditure surveys (HCESs) such as the IHS3 are increasingly being used to address the food and nutrition information gap (Imhoff-Kunsch et al. 2012; Jariseta *et al*., 2012). Fiedler *et al*. (2013) argue that HCESs are comprehensive, representative, low-cost and routine.

To date, relatively few studies have reported the use of HCESs to calculate calorie and micronutrient deficiencies (Bermudez *et al*., 2012; Verduzco-Gallo *et al*., 2014). This study applied the methodology outlined by both Smith and Subandoro (2007) and Bermudez et al. (2012) to calculate the prevalence of calorie and micronutrient deficiencies, respectively. Results for calorie deficiencies are comparable with studies by Smith *et al*. (2006). More recently however, Verduzco-Gallo *et al*. (2014) analysed the same IHS3 dataset and reported a calorie deficiency of 38.6% for rural Southern Malawi, a difference of over 25 percentage points when compared with calorie deficiency estimates (64.2%) reported in Table 2.4.

A number of factors may account for the disparity, including the use of different sampling strategies, data cleaning procedures and food composition tables. Indeed, the removal of households with implausible calorie consumption levels has proved particularly problematic. Over 17% of the original study sample had to be removed when following cut-off points defined by Bermudez et al. (2012). Under these guidelines, households with less than 500 and greater than 6000 kcal per household member are omitted. The large proportion of excluded households implies that either the data quality is poor, or that calorie intakes above 6000 and below 500 kcal per capita may be plausible on a short-term basis. The seasonal nature of food security within developing countries is documented to lead to significantly high and low calorie intakes during the harvest and hunger seasons, respectively (Hillbruner and Egan, 2008). Variability in the data set may reflect this, making the assumption that all of the extreme values are due to sampling error or artefacts of data interpretation invalid. Using fixed values to define calorie intakes that are biologically plausible will neglect physiological and temporal aspects of an individual's calorie needs.

Other factors accounting for differences in reported deficiency values include disagreement between the selection of cut-off points for calorie and micronutrient requirements, compounded by subtle differences in the methodology to calculate deficiencies. In order for indicators of food security to be comparable across studies, future work must agree upon standard methodologies, metrics and cut-off points. More work to develop locally specific conversion tables is also urgently needed to provide a more reliable understanding of calorie and micronutrient outcomes of food security strategies.

2.4.3 Implications for Policy

With the widespread recognition of the heterogeneous nature of communities, there is growing support for the use of household typologies in the design and targeting of policy instruments and extension programmes (Daskalopoulou and Petrou, 2002; Williams *et al.*, 2015). The application of household typologies has potential to improve the efficiency of rural development programmes (Emtage *et al.*, 2007). By understanding the livelihoods of households it is possible to design programmes to meet specific needs. Typologies may also offer a framework through which to identify farmer interest groups. This could prove useful in the initial stages of a project where the engagement of households may aid the design and implementation of policy and/ or extension programmes. It may also act to enhance monitoring and evaluation stages of such projects.

Although future work is needed to test whether the use of typologies to direct food security policy leads to better outcomes, here we hypothesise how the typology developed in this case study might be used to guide food policy for farmers, agricultural labourers and non-agricultural workers within rural Southern Malawi.

2.4.3.1 Agricultural Labourers

This group generally had the least assets and the worst food security outcomes, thus placing them squarely in the 'hanging-in' category of Dorward *et al.* (2006), for whom social protection measures may play an integral role in the alleviation of food insecurity. Attention should be given to cash and food transfer programmes including employment-based safety nets, social pensions and school feeding programmes. Deveraux (2001) recognises the wide-ranging benefits of such social protection measures. Regular cash transfers for instance, can promote investment in agriculture, lead to the informal redistribution of wealth within social networks and encourage local trade (Devereux 2001).

2.4.3.2 Farmers

The farmer group in this case study had the best natural capital endowments but were relatively weak in their human, social and financial capitals. Their food security outcomes were generally intermediate between the other two groups but were highly variable across the year. To enhance the food security outcomes of this group, policies are needed that support them in 'stepping-up' and investing more in farming (Dorward *et al*., 2006). These could include a focus on the growth of human capital. Improved access to education can heighten the capacity of farmers to adopt more advanced crop management techniques and improve farm productivity. Furthermore, education can act as a gateway into non-agricultural work and result in the expansion of household income.

Increases in farm productivity could also be met by driving investment in physical capital through improved access to institutional credit. Regarding natural capital, there is a need to focus research and policy efforts upon rain-fed agriculture. According to Rosegrant and Cline (2014) advances in water harvesting technologies, crop breeding and extension services, combined with good access to markets may allow farmers to exploit the full potential of rain-fed agriculture.

2.4.3.3 Non-agricultural Workers

Non-agricultural workers in this case study tended to have the highest asset endowments and best food security outcomes, suggesting they were in the process of 'stepping-out' of agriculture, a group for which Dorward *et al*. (2006) recommend policies to increase resilience. These could support increased labour opportunities for non-agricultural work. Attention should also be focused upon enhancing infrastructure to improve market access. There is evidence to suggest that roads may strengthen links between agricultural and non-agricultural activities within rural areas (Gachassin *et al*., 2015). Given the relatively higher financial assets of this group, agricultural input subsidies, as currently provided in Malawi, are likely to be less useful to them than supporting efficient local markets.

Results from this study uncovered a link between livelihood strategies and gender. The proportion of female-headed households was significantly lower for non-agricultural workers when compared with farmers and agricultural labourers. In order to bridge this gender gap, policies that empower female-headed households should be favoured. A study by Swaminathan (2010) found access to credit increased the status of women and financed off-farm wage or self-employment activities. Another finding of this study is the variability in food security outcomes across the year for all three groups, with fluctuations particularly high before and after the maize harvest. This suggests a general focus for food policies on greater diversification of crops.

2.5 Conclusions

Overcoming hunger and malnutrition remains a challenge in many developing countries. The creation of household typologies may aid in the design of more effective policy instruments. This study has illustrated how data collected through the standard Integrated Household Survey, applied in many countries, can be used to create a typology of households that may support policy-making. In rural Southern Malawi this gave rise to three groups who differ particularly in the activities to which they allocate their household labour. Application of the SLF enabled us to capture the complexity of household food security and highlighted variation in the livelihoods of the different household groups, which should be considered when developing policy interventions. Key methodological challenges that remain relate to the need for agreement on cut-off points for food security indicators, more reliable local conversion tables and detailed consumption data that takes into account intra-household allocation of food. These results also provide only a snapshot in time. Planned work by the authors will therefore use the household typology as a basis for simulation development. Ultimately, it is hoped that this will enable policy-makers to take into account the dynamic nature of household food security and support more effective targeting of appropriate interventions to promote food security for all.

2.6 Supplementary Information

Table 2.5: Results of the cluster analysis performed with the validation dataset (n = 808)

	Full Sample		Cluster 1 Farmers		Cluster 2 Agricultural labourers		Cluster 3 Non-agricultural workers	
n	808		500		129		179	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Family Labour (activity time/ total family labour)								
On-farm work	0.69	0.013	$0.94^{(2,3)}$	0.005	$0.32^{(1,3)}$	0.021	$0.25^{(1,2)}$	0.015
Off-farm agricultural work	0.13	0.009	$0.03^{(2)}$	0.004	$0.65^{(1,3)}$	0.021	$0.02^{(2)}$	0.005
Off-farm non-agricultural work	0.18	0.011	$0.02^{(3)}$	0.003	$0.03^{(3)}$	0.008	$0.73^{(1,2)}$	0.015
Cultivated Land (ha/household member)								
Land area	0.19	0.009	0.21	0.013	0.17	0.014	0.16	0.012
Livestock Assets (number of livestock owned per household)								
Livestock	1.2	0.105	$1.5^{(2)}$	0.153	$0.08^{(1,3)}$	0.083	$1.03^{(2)}$	0.186
Poultry	3.1	0.252	$3.5^{(2)}$	0.366	$0.28^{(1,3)}$	0.279	$3.41^{(2)}$	0.443
Gender (proportion of female headed households, %)								
Proportion of female headed households	26.7		$30.4^{(3)}$		21.7		$20.1^{(1)}$	

Chapter 3: Agent-based Modelling to Assess Community Food Security and Sustainable Livelihoods

Abstract

Conventional policies, institutions and transforming processes have failed to eradicate food insecurity within developing countries. Complex social, ecological and economic processes have been overlooked. Interactions between households and the environment lead to the emergence of community food security, an evolving concept that advocates long-term systemic approaches to address food security in an equitable manner. Agent-based models are well suited to address the multi-scalar, dynamic nature of community food security. We present a methodological approach for constructing an agent-based model to assess community food security and variation among livelihood trajectories using rural Malawi as a case study. The approach integrates both quantitative and qualitative data to explore how interactions between households and the environment lead to the emergence of community food availability, access, utilisation and stability over time. Results suggest that livelihoods based upon either non-agricultural work or farming are most stable over time, but agricultural labourers, dependent upon the availability of casual work, demonstrate limited capacity to 'step-up' livelihood activities. The scenario analysis shows that population growth and increased rainfall variability are linked to significant declines in food utilisation and stability by 2050. Taking a systems approach may help to enhance the sustainability of livelihoods, target efforts and promote community food security. We discuss transferability of the methodological approach to other case studies and scenarios.

Key words: social-ecological systems, livelihood trajectories, nutrition, Malawi, food security

3.1 Introduction

The aim of this chapter is to develop a methodological approach to enable the construction of ABMs of community food security in developing country contexts where regional data sets are available. Measurement of food security has tended to concentrate on either entire nations or individual households (Pinstrup-Andersen, 2009; Carletto *et al*., 2013). However, rights-based approaches have prompted a renewed interest in community food security, an evolving concept that advocates long-term systemic approaches to address food insecurity in an equitable and sustainable manner (Jarosz, 2014). Community food security can be defined as *"a situation in which all community residents obtain a safe, culturally acceptable, nutritionally adequate diet* *through a sustainable food system that maximizes self-reliance and social justice"* (Hamm and Bellows, 2003, p.37). It differs from household or national food security, as it emphasises the complex nature of food systems, which are embedded within dynamic social, ecological and economic processes (Thompson and Scoones, 2009; Kaiser, 2011). Community food security pays attention to interactions between system components such as households, institutions and the environment and the emergence of diverse food systems and food security outcomes (Hamm and Bellows, 2003; McCullum *et al*., 2005) .

The inherent complexity of community food security poses a significant challenge to the design and implementation of appropriate development programmes and policy (McCullum *et al*., 2005). Indeed, community food security is an emergent property of household food security, which is shaped by the way in which households interact, acquire and utilize assets within a context of vulnerability. The multiple interactions between the various factors that affect the livelihoods of households give rise to often complex and non-linear system behaviour (Chambers and Conway 1991; Scoones, 1998).

Within developing countries, the livelihoods of rural households remain largely dependent upon agriculture. This chapter uses rural Malawi as a case study. Malawi is a small, landlocked country home to approximately 17 million people (World Bank 2016). In lieu of major natural resources, agriculture is regarded as the most important sector (Sahley *et al*., 2005). More than 90% of the rural population are smallholder farmers, responsible for cultivating plots with an average size of just 0.8 hectares (NSO, 2012b).

Maize is the dominant crop of the smallholder sector and the staple diet of the population (NSO, 2012b). According to Chisinga *et al*. (2012), although over 97% of smallholder farmers grow maize, only 10% are net sellers and up to 60% are net buyers. Between the months of November and March there is a single rainy (growing) season, followed by a dry season from April to October (Orr *et al*., 2009). Smallholders with access to dimba fields located in the valley bottoms (dambos) may take advantage of residual moisture and extend maize cultivation beyond the end of the rains (Orr *et al*., 2009). However, access to dimba fields is limited and the vast majority of agriculture remains rainfed, leaving farmers vulnerable to climatic shocks and food insecurity (Sahley *et al*., 2005).

Over time, food insecurity is compounded by additional exogenous trends such as population growth (De Sherbinin *et al*., 2009) and climate change (Schmidhuber and Tubiello, 2007). The discourse on climate change impacts and food in Africa has tended to focus on changes in crop yields and food production (Knox *et al*., 2012; Cairns *et al*., 2013; Folberth *et al*., 2014). According to Connolly-Boutin and Smit (2015) however, attention must be paid to the multidimensional nature of food security.

A total of four dimensions are recognised under the ‘four pillars’ framework, including availability, access, utilisation and stability. Here, the production of food is related primarily to food availability (Headey and Ecker, 2013). Access refers to the amount of food a household can produce, purchase from the market and/or derive from other means (Burchi and Muro, 2016). Households might draw upon social safety nets such as food for work programmes or adopt coping strategies like selling livestock or borrowing food (Devereux, 2016). A third dimension, utilisation, refers to the ability of households to process accessible food. This is dependent upon the household’s ability to obtain sufficient quantities of fuel and clean water. Utilisation also relates to the physiological capability of individuals to digest food. This is affected by health and wellbeing (Jones *et al*., 2013). Finally, stability dictates how robust availability, access and utilisation dimensions are to shocks and stresses over time (Burchi and Muro, 2016).

In response to shocks and stresses, households may adjust their livelihood activities to ensure sufficient food security (Tittonell, 2014). This results in four main trajectories in which households may be seen to ‘hang-in’, ‘step-up’, ‘step-out’ or ‘fall-down’. Households that are able to maintain and protect current levels of wealth and welfare for example, are considered to be ‘hanging-in’ (Dorward *et al*., 2009). Those who are able invest in assets to expand the scale or productivity of existing activities are regarded to be ‘stepping-up’ (Dorward *et al*., 2009). The term ‘stepping-out’ refers to cases whereby the accumulation of assets permits households to shift into new, more productive activities (Dorward *et al*., 2009). Households following the opposite trajectory however, of deteriorating assets and a shift towards less productive activities are considered to be ‘falling-down’ (Falconnier *et al*., 2015). A livelihood is deemed sustainable by Chambers and Conway (1991, p.26) *“when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets and provide sustainable livelihood opportunities for the next generation and which contributes net benefits to other livelihoods at the local and global levels and in the short and long term”.*

Assessment of community food security is challenged by scarcity of data at the community level. Within Malawi, since 1990 the National Statistical Office has conducted integrated household surveys every five years. The surveys have provided a wealth of information on the socio-economic status of households within Malawi. However, a district level sampling frame means that data are not representative at village level. Compared with Integrated Household Surveys, the collection of village level data within Malawi has typically been uncoordinated and is not easily available in the literature.

Greater understanding of the relationships amongst climate, population, food and livelihoods is necessary to guide policy programmes and actions intended to sustain or improve the livelihoods and food security of communities in many developing countries and smallholder dominated areas. The applied questions that motivated this research are: how do interactions between households and the environment lead to the emergence of community food security? How is increased rainfall variability and population growth likely to impact future food availability, access, utilisation and stability? And how will increased rainfall variability and population growth affect household livelihood trajectories over time?

3.2 The Potential of Agent-based Modelling

Agent-based modelling provides a useful simulation tool to explore the dynamics of social-ecological systems (Balbi and Giupponi, 2010). It represents a bottom-up approach in which interactions at the local level lead to the emergence of patterns at the macro-level (Epstein and Axtell, 1996). Agent-based simulations enable the heterogeneous nature of households, individuals and the environment to be taken into account (Epstein, 1999). ABMs also employ a dynamic approach that allows the trajectory of households and individuals to be traced over time (Valbuena *et al*., 2008; Valbuena *et al*., 2009). A key advantage of the technique is its ability to represent decision-making and behaviour (Smajgl *et al*., 2011; Smajgl and Bohensky, 2013). Finally, ABMs can integrate data from multiple sources, both qualitative and quantitative, which is particularly useful within data scarce contexts (Janssen and Ostrom, 2006; Robinson *et al*., 2007). In data poor regions, such as our case study area of southern Malawi, we suggest that the scarcity of community or village data can be overcome using a typology-based approach. The ABM can be built upon regional data that tends to be more easily available. This chapter demonstrates how the ABM can then be supplemented with context specific data to tailor development programmes and policies that address community food security.

For simulation outputs to be of use to decision makers, the model must be credible (Verburg *et al*., 2015). A range of technical, methodological and epistemological uncertainties may act to undermine model credibility (Funtowicz and Ravetz, 1990). According to Reilly & Willenbockel (2010), technical uncertainties relate to the quality of data available to calibrate the model. Methodological uncertainties arise from knowledge constraints. There may not be sufficient knowledge with which to construct an accurate representation of the system at hand. Finally, epistemological uncertainties are concerned with model completeness. A number of factors, including stochasticity inherent to social-ecological systems, changes in human behaviour, technological innovations and 'black swan' events, may pose great uncertainty over time (Reilly and Willenbockel, 2010). In order to ensure model credibility, uncertainty analysis can build confidence that outcomes are representative of the complex social ecological system at hand, rather than artefacts of parameterisation. In the present case, we use expert knowledge and empirical data to validate the model both quantitatively and qualitatively.

The chapter begins with a description of the study site and modelling approach. Initial results from scenarios investigating the effects of population growth, rainfall variability and market projections on food security are presented in Section 3.3. Section 3.4 provides an evaluation of the modelling approach and discusses insights gained regarding the status of community food security, using rural Malawi as a case study.

3.3 Study Site and Methodology

This study analyses rural households located within Southern Malawi. Over 50% of the population live on less than one US dollar a day and the proportion of ultra-poor people (defined as the proportion of the population below the minimum level of dietary energy requirement) is highest within Southern Malawi at approximately 34.2% (Gondwe, 2014). Villages within rural Malawi are highly heterogeneous. Households differ with regards to the assets they possess and the trends, shocks and seasonal shifts they are exposed to (Kamanga *et al.*, 2009; Chilongo, 2014).

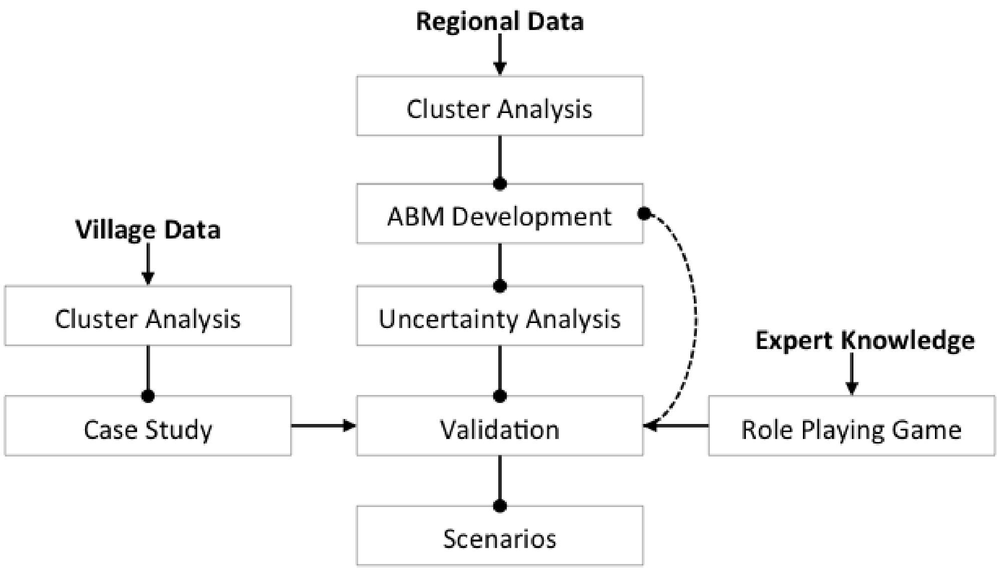

Figure 3.1: An overview of the modelling approach.

Two exogenous drivers, population growth and climate change, appear to be highly relevant to food security outcomes. Africa is the only region in the world expected to demonstrate sustained population growth until 2050 (Jayne *et al.*, 2014). In Malawi, the rural population is anticipated to grow from approximately 8.4 million in 1990 to almost 29 million by 2050 (UN, 2015c). The share of young people is also increasing over time (UN, 2015c). Within Africa as a whole, Fine *et al*. (2012) estimate that approximately 122 million people will enter the labour force between 2010 and 2020. Over the same period it is estimated that the non-farm sectors will generate just 70 million wage jobs (Fine *et al*., 2012). Agricultural work will therefore remain an important livelihood strategy for Africa's expanding young labour force. Climate change provides an additional stressor affecting livelihoods and food security (Connolly-Boutin and Smit, 2015). Here, changes to climatic patterns manifest over longer time frames, whilst changes in the frequency and severity of extreme weather events can be felt over shorter time periods.

The modelling approach comprised a number of stages (Fig. 3.1) with different data sources incorporated into each. The remainder of this section introduces the data sources before moving on to summarise each of the stages of the approach.

3.3.1 Data Sources

3.3.1.1 Regional Data

Regional data for this study came from Malawi's Third Integrated Household Survey (IHS3) (NSO, 2012a). The National Statistical Office of Malawi conducted the survey from March 2010 to March 2011. The main objective of the IHS3 was to provide and update information on the welfare and socio-economic status of Malawian households. Four questionnaire instruments were employed including household, agriculture, fishery and community questionnaires. The survey selected households based on a two-stage stratified sampling process and a probability proportional to size design. As a result, the sample was representative at national as well as district levels. A total of 12271 households were sampled, made up of a cross-sectional sample set (74%) and a smaller, panel sample set (26%). Cross-sectional households were visited once in 2010/11, whereas panel households were visited twice: once in 2010/11 and again in 2013. The panel sample wasn't publicly available at the time of our study. Instead, cross-sectional households from rural areas of southern Malawi were extracted to give a sample of 3840 households. This data was utilised throughout ABM development in order to construct a hypothetical village within southern Malawi.

3.3.1.2 Village Data

Household-level data for a village in Southern Malawi was collected over a period of four days in July 2015 as part of a larger research project. Four trained Malawian enumerators used a household questionnaire to collect information on farming practices, crops planted, harvested and sold, other income generating activities, perceived food security, and socio-demographic characteristics of the households. After a village mapping exercise, in which three village representatives listed the household heads and mapped their locations, all households (n=46) were selected (census) to participate. When the listed household head was not available, the partner or another adult (18 years or above) was interviewed. Three households were not home and therefore not interviewed. This data was used for parameterisation purposes as described in Section 3.3.4.

3.3.1.3 Expert Knowledge

This study benefits from an informal association with the project ASSETS, which aims to *"explicitly quantify the linkages between ecosystem services that affect and are affected by food security and nutritional health for the rural poor at the forest-agricultural interface"* (http://espa-assets.org/). Expert knowledge was drawn from project partners at the University of Southampton and LEAD-SEA, Malawi, throughout the modelling design process to iteratively validate the structure of the ABM and test the decision rules of agents.

3.3.2 Cluster Analysis

A cluster analysis was performed twice, once during the initial model design stages and again as part of the validation process. The initial cluster analysis used regional data to construct a typology of households within rural Southern Malawi (See Dobbie *et al*. in review). Using variables based upon land, labour, livestock assets and gender, three distinct clusters were identified and labelled: farmers, agricultural labourers and non-agricultural workers, respectively (Dobbie *et al*. in review). A subsequent cluster analysis used the same variables to enable the integration of village data into the model. This provided a village-level case study, which formed a key component of the validation process.

3.3.3 ABM Development

The initial model development process involved a number of iterative steps, including i) clarification of model aim, ii) conceptual model development, iii) design and implementation of the ABM, and iv) validation. A detailed explanation of the model process is provided by Dobbie and Balbi (2017). A number of improvements have since been made to the model, which is presented here using the Overview, Design, Details and Decision Making (ODD+D) protocol (Müller *et al*., 2013). The model will shortly be available online (https://www.openabm.org/model/5170/version/1/view).

3.3.3.1 Overview

Purpose

The purpose of the model is to simulate the behaviour of households within a village and observe the emerging properties of the system in terms of food security. The model draws upon the SLF (Chambers and Conway, 1991; Scoones, 1998) to consider food security outcomes of different livelihood strategies. A key aim of the model is to quantify the multiple dimensions of food security (namely food availability, access, utilisation and stability) at both the household and village level. The model is designed to be used and developed by scientists and stakeholders to explore: i) how interactions between households and the environment may lead to the emergence of community food security; ii) the impact of increased rainfall variability and population growth on future food availability, access, utilisation and stability; iii) the effect of increased rainfall variability and population growth upon household livelihood trajectories over time.

Entities, State Variables and Scales

Households are the main entity and are divided into three types i) farmers, ii) agricultural labourers and iii) non-agricultural workers. The main attributes of households include human, physical, natural and financial capital. Individuals belong to households and are defined by their gender, education, and age. Households and individuals are initialised using empirical data from the third household survey (IHS3) for Malawi (NSO, 2012) and as a result are highly heterogeneous. The total number of households at initialization is 116 (the average number of households per village in Southern Malawi in 2010).

Households interact through a social network, which is modelled as a 'small world' with characteristically short average path lengths and high clustering (Watz and Strogatz, 1998). The social network is used by the households to access labour opportunities and food donations. This assumption is based upon results from the IHS3 data combined with evidence from the literature (Gebremedhin *et al*., 2010; Spielman *et al*., 2011; Ligon and Schechter, 2012; NSO, 2012a). The social network is initialized with an average degree of 9.5, an average path slightly above 2 and an average clustering coefficient of 0.64.

The current environment represents a hypothetical village within Southern Malawi. Based upon IHS3 data, the village encompasses approximately 199 hectares made up of farmland, *dimba*[1], forest and water. At initialization farmland is set at around 60 ha (making it less than a hectare per farmer) while forest area is set at 135 ha in total. The environment is represented as a stylised 2D grid of patches with each patch corresponding to an area of land of variable size. Key attributes of the different patches include: size (in hectares), fertility (kg of fertiliser applied) and ownership. These are initialised using plot level data from the IHS3 (NSO, 2012a). Households can own both *dimba* and farm plots, whilst forests and water remain communal. The model runs on a monthly time-step. The location of patches and individuals or households has no effect on model outcomes as it is assumed that the village boundary is small enough for individuals (and households) to access farm plots, *dimba* and forest within any given month. Other entities are captured in Figure 3.2 and a more detailed description and justification of the state variables that characterise each entity is provided as part of model documentation online.

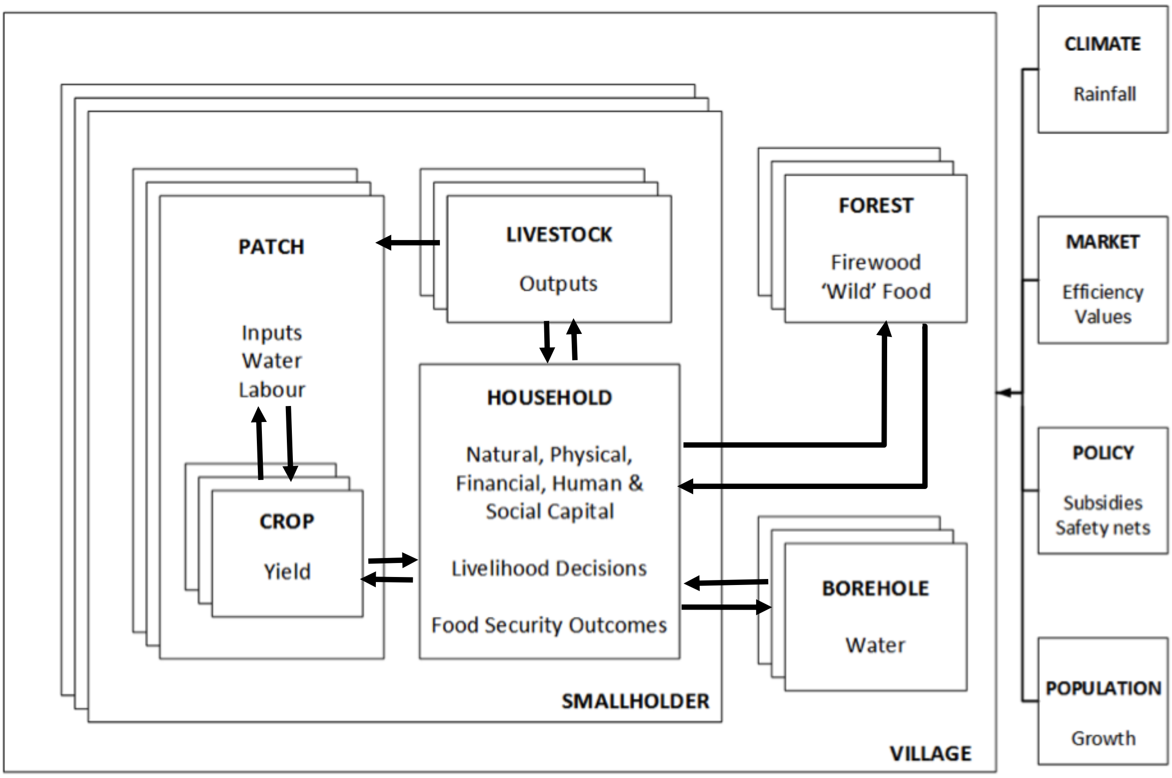

Figure 3.2: Key entities in the village food security model and the relationships between them.

[1] Farm plots typically found in areas bordering streams and rivers. Residual moisture means they can be cultivated during the dry season from April to October.

3.3.3.2 Process, Overview and Scheduling

During each monthly time step households go through a sequence of processes from resource allocation to harvesting and adopting coping strategies which combine to give village-level outcomes in relation to land use, food production and food security status (Fig. 3.3). During simulations described here, the model loops through 480 months, representing 40 years from 2010 to 2050.

Each time-step begins by defining the month of the year and the corresponding agricultural season. Basic needs, defined in the IHS3 in the form of food, water and fuel, are then calculated for each of the households. Household labour is allocated between productive activities, including firewood collection, water collection, on-farm agricultural activities, off-farm agricultural activities and off-farm non-agricultural work.

At the beginning of the agricultural season, households make land use decisions. Eleven different combinations of basic grains, annual roots, permanent roots, nuts & pulses, fruit trees, vegetables and cash crops are possible. Decisions are constrained by land, labour, subsistence, input and knowledge requirements. In the months that follow, households are able to adjust land allocation decisions based upon labour availability. In addition to farming, households may also tend livestock, forage for wild and indigenous foods and carry out off-farm agricultural activities such as casual farm labour (ganyu) and non-agricultural employment.

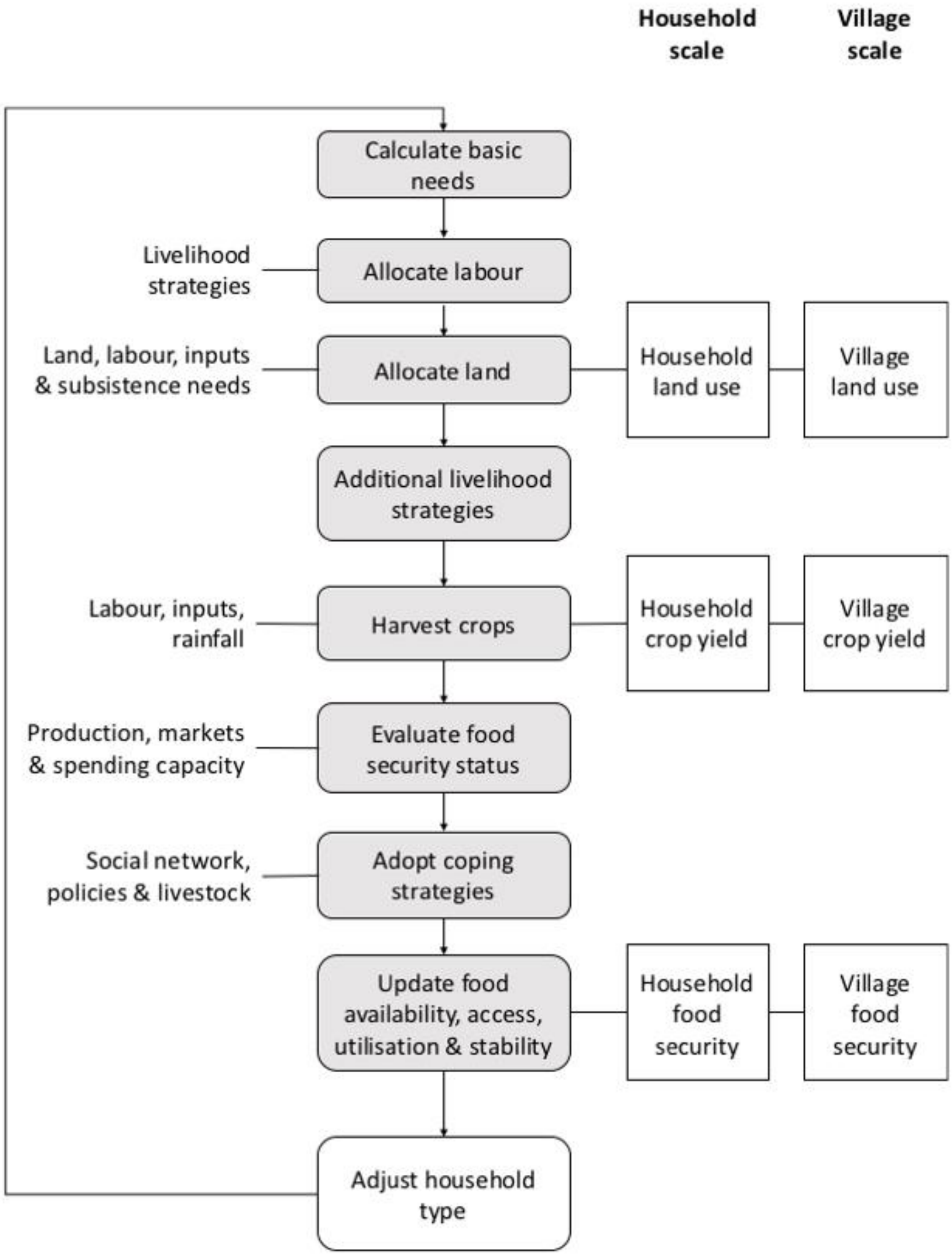

Figure 3.3: The sequence of processes conducted by each household during a monthly time-step. Inputs are listed on the left-hand side and outcomes on the right. Outcome variables at the household level can be aggregated to give indicators of land use, productivity and food security at the village level.

Towards the end of the time-step the four dimensions of food security, namely availability, access, utilisation and stability, are quantified for each household. Food availability is determined based upon the amount of calories available from self-production and the market. The total number of calories from crops, livestock products and forage is first summed. Surplus calories are then calculated as the difference between food-needs and calories from food availability and spending capacity (the difference between household income and non-food expenses). If surplus is greater than zero it is divided into a calorie-pool that can be donated to members of a household's social network. If surplus is less than zero it is converted into a calorie deficit.

Food access is defined by the amount of calories accessible from food production, market purchases and coping strategies. It is calculated as a sum of equivalent calories from food production, spending capacity, payment for work programmes, borrowing food from the social network and sale of livestock. The ability of a household to process this food dictates food utilisation. Potential calories are determined by food access. Actual calories can then be calculated by multiplying potential calories by the processability value. This is a percentage value that takes into account the proportion of water and fuel needs the household has met, as well as household health. Whether food needs of the household have been met or not is then determined and stocks of water and fuel are also updated.

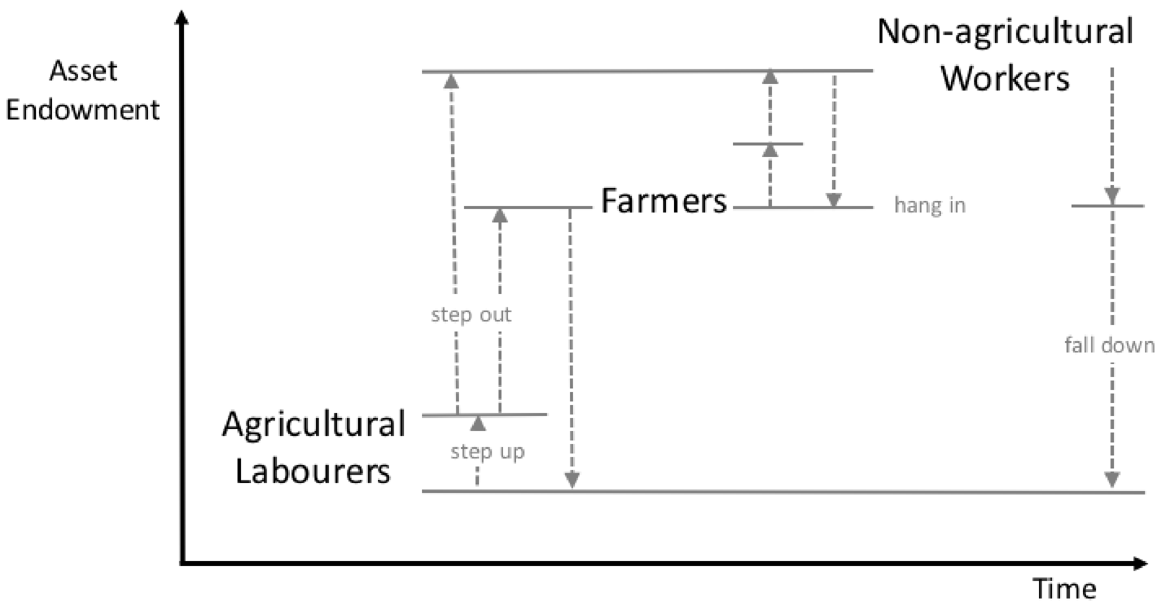

Figure 3.4: Conceptual diagram of household trajectories. Over time households may hang in, step up, step out or fall down.

Food stability is a function of market stability, political stability and production stability. Market stability is defined as the coefficient of variation (CV) in annual maize price. Political stability is a global variable calculated as the mean of the CV of the proportion of households with access to inputs and the CV of households with access to payment for work schemes (Beegle *et al.*, 2014). Production stability is a local variable calculated as the CV of household maize output for the given month. This allows multiple scales to be taken into account when evaluating food stability. Finally, food security is determined based upon food availability, access, utilisation and stability.

Using techniques from fuzzy logic (Zadeh, 1996; Bosma *et al*., 2012), each household returns a value between 0 and 100 with 0 being the lowest and 100, the highest.

A total of 12 time-steps constitute an agricultural season, running from June to May the following year. The livelihood strategy, or 'type' of a household may be adjusted at the end of an agricultural season. This is based upon the proportion of time allocated to farming, agricultural labour and non-agricultural work. In line with Dorward (2009), households persevering with the same livelihood strategy, or type are considered to be 'hanging-in', those households who move to a type of higher yields and/ or income are classified as 'stepping-up' and households shifting into new, more productive activities are termed 'stepping-out'. Households following a trajectory of declining yields and income are regarded to be 'falling down' (Fig 3.4).

3.3.3.3 Design Concepts

Theoretical and Empirical Background

The model is designed based upon the sustainable livelihoods framework as described by Chambers and Conway (1991). Under the framework, household food security is viewed as the outcome of livelihood strategies (Chambers and Conway, 1991). These emerge from complex interactions and feedbacks between transforming structures and processes (e.g. policies), which occur within a context of vulnerability and shape the human, natural, financial and social capital of households (Chambers and Conway, 1991).

The overlapping nature of food availability, access, utilisation and stability pose problems when constructing a quantitative model. In order to operationalise the 'four pillars' of food security, we adapted the FAO framework to form a well-defined hierarchy (Fig. 3.5). Artificial boundaries were drawn across the four dimensions, with links made to the attributes and activities of households, as well as the impact of exogenous factors such as climate stability and water and firewood availability. The framework ensures that availability of food is necessary for household food security, but is not sufficient to guarantee access without accounting for its stability. Similarly, food access is also required for household food security, but not sufficient to ensure adequate utilisation.

A conscious effort was made to depart from the notion of economic agents. Earlier agricultural household models have tended to favour 'rational' representations of decision making (see Dorward, 1991; Doward, 2006; Mouysset *et al*., 2011). These models assume that a rational agent, endowed with clear preferences and all available information, will elect the optimum solution with no associated cost (Gigerenzer and Todd, 1999). There is growing evidence however, that farming households are seldom efficient maximisers (Roncoli *et al*., 2002; Schreinemachers and Berger, 2006; Kalanda-Joshua *et al*., 2011). Participatory, field-based techniques such as ethnographic decision tree modelling may be used to identify simple rules of thumb used in the decision making process (Gladwin, 1979; Thangata *et al*., 2002). However, this approach may not be feasible within research environments characterised by data scarcity and time constraints. It is for this reason that for this study we have adopted an approach described by Deadman *et al*. (2004).

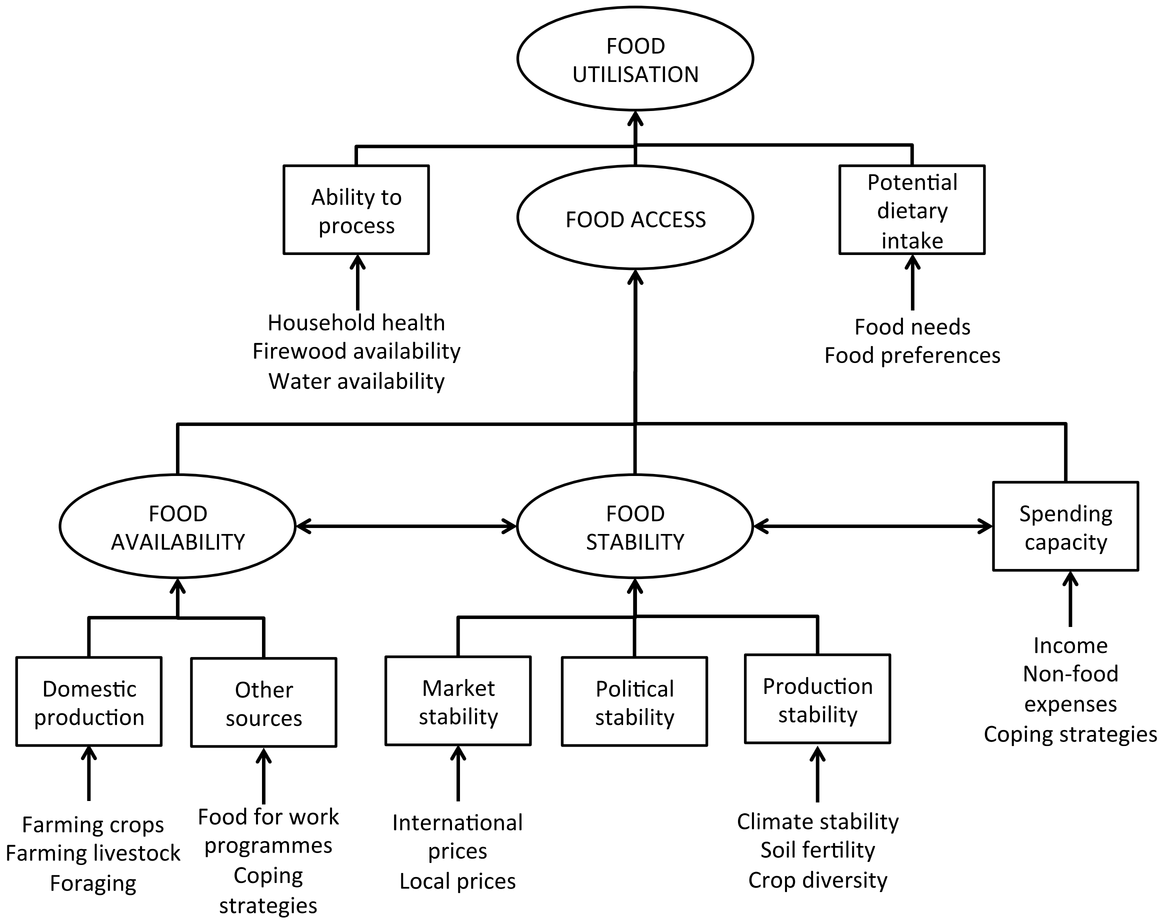

Figure 3.5: The four pillars of food security as an operational framework.

In order to develop LUCITA, an ABM of land use change in the Amazon rainforest, Deadman *et al*. (2004) used survey data to construct simple decision trees. On the basis of subsistence requirements, endowments and soil quality, household agents used simple 'if-then' rules to decide whether to leave areas of land to fallow, plant annuals, perennials, or pasture (Deadman *et al*., 2004). Compared to other models based on 'black box' strategies such as genetic algorithms, and classifier systems, a heuristic decision tree is transparent, more easily verified and validated (Gigerenzer and Todd, 1999).

For our ABM, data from participatory rural appraisals (PRA) collected by ASSETS (Schreckenberg *et* al., 2016) was used to develop qualitative decision trees underpinning key activities such as land use. These were then parameterised for each of the three household types (farmers, agricultural labourers and non-agricultural workers) using quantitative data from the clustered IHS3 survey. Once constructed and parameterised, the decision trees were validated using expert knowledge and role playing games (see Section 3.3.5). An example of the decision tree for land use change is given below (Fig. 3.6.).

Decision-making

Households are driven by their need to achieve food security in terms of calories. Livelihood choices and strategies are dictated by household type, i.e. farmer, agricultural labourer or non-agricultural worker. The procedure in which households set long-term land allocation decisions occurs at the start of the growing season. Using simple decision trees calibrated for each household typology, households choose between 11 combinations of 6 different crop types for each patch of land they own. Decisions are constrained by land, labour, subsistence, input and knowledge requirements (Fig. 3.6).

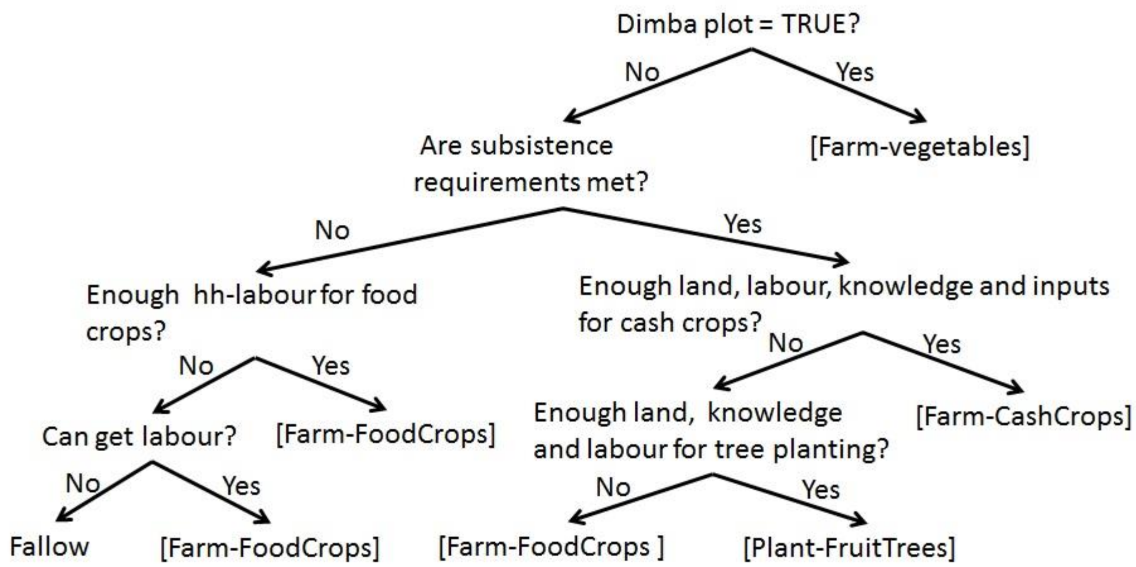

Figure 3.6: Land allocation decision tree

If the requirements are met, the household goes on to allocate land according to the farm-vegetables, farm-food-crops, farm-cash-crops or plant-fruit-trees sub-procedures. If labour requirements are not met, households can use the seek-labour sub-procedure to hire labour from their social network, otherwise the land is left to fallow using the fallow sub-procedure.

When following the sub-procedure 'farm-food-crops' each household selects a crop pattern with a likelihood that is dependent on the household type (Fig. 3.7). Households will adjust their labour and land availability accordingly, while accounting for an increased level of subsistence.

Get weighted list of cropping patterns for hh-type

↓

Pick random integer from 0 to l00

↓

Select corresponding crop pattern

↓

Allocate land
Decrease hh-labour
Decrease hh-land
Increase subsistence

Crop Pattern	Weighting		
	farmers	agri-labourers	non-agri-workers
Basic grains	0 - 42	0 - 51	0 - 36
Nuts & pulses	43 - 46	52 - 53	37 - 39
Annual roots	47	54	40
Perm roots	48 - 52	55 - 59	41 - 44
Basic grains with nuts and pulses	53 - 100	60 - 100	45 - 100

Figure 3.7: Selection of different cropping patterns using the 'farm-food-crops' sub procedure.

At each time-step households may employ adaptation mechanisms. These include reducing or increasing the area of land cultivated based upon available labour, as well as adopting coping strategies if the supply of calories is too low. At the end of an agricultural season, the livelihood strategy, or 'type' of a household may be adjusted to reflect changes in the proportion of time spent upon farming, agricultural labour and non-agricultural work (see section 3.3.3.4). No learning is included in the version of the model described here.

Sensing

Households are aware of their own variables, including subsistence needs and labour availability. These variables are important when making land allocation decisions. In addition, households are aware of their access to calories. In times of calorie deficits they may opt to carry out coping strategies. In some contexts, households may also be able to sense variables associated with other households within their social network, as well as other entities such as institutions. When considering how much firewood to extract from the forest for instance, households take into account both the past extraction habits of others, as well as the sustainable extraction levels suggested by institutions.

Prediction

Households do not make predictions instead they react to information as it becomes available. The cultivation of land for example, is adjusted based upon frequent assessments of present labour availability rather than expectations regarding future labour endowments.

Interaction

The majority of model procedures describe interactions between households and the environment. These include those associated with land use and resource extraction. Households may also interact with each other through a social network to exchange land, labour, and/ or calories.

Collectives

There are three main collectives in this version of the model: i) households are aggregates of individuals, ii) social networks emerge from linked households and iii) farms consist of patches of farmland and dimba owned by a single household.

Stochasticity

Stochasticity is present within multiple model procedures. During initialisation the majority of model parameters are assigned empirically by reading in survey data. However, in a handful of cases where data was found to be insufficient, random number distributions were used to assign variables. Once the model starts iterating, a stochastic mechanism is used to determine how households allocate land to different crop types. For a few activity-based procedures such as foraging for wild food, the output for each unit of labour is drawn from a distribution consistent with survey data. The order in which households approach other households within their social network is also stochastic.

Observation

Several village-level features emerge from interactions between households and the environment. These include i) land use patterns ii) crop productivity and iii) food security status. Following each monthly time step, a number of low-level and aggregated variables are collected and written to output files. Attention is given to the food security outcomes of the three different livelihood strategies: farmers, agricultural labourers and non-agricultural workers.

3.3.3.4 Model Details

This section discusses the main sub-models in greater detail.

Main sub-models

Calculate basic needs. This sub-model calculates the food, water and fuel needs of a household. In order to calculate household calorie requirements, daily recommended calorie intake for each individual must first be evaluated, taking into account age and gender. Values are based upon those published in Smith and Subandoro (2007) for light activity. The daily calorie requirements of individuals are then summed for each household and multiplied by 30 days to yield monthly calorie requirements. In order to quantify water needs in litres, household size is multiplied by 1080, based upon GoM (2009) recommendations of 36 litres per capita per day (multiplied by 30 days). Finally fuel requirements in cubic meters of firewood are calculated using a simple subsistence equation described by Agrawal *et al*. (2013):

$$s = (hs \cdot w)/(e \cdot d) \qquad (3.1)$$

where *hs* is the size of household, *w* is the per capita energy requirement for cooking per month, *e* is the energy content of the wood and *d* is the average density of miombo tree species.

Update labour allocation. A sub-model to distribute labour between productive activities, including: firewood collection, water collection, on-farm agricultural activities, off-farm agricultural work and off-farm non-agricultural work. Total labour availability (in hours per month) is first calculated for the household. This is based upon the household type (farmer, agricultural labourer or non-agricultural worker), number of working adults, gender and health. The proportion of time spent by the household on different productive activities is then determined. Proportions are set according to household type using averages calculated from IHS3 data.

Update land allocation. At the start of the agricultural season, households set long-term land allocation decisions. Using simple decision trees calibrated for each household type, for each patch of land owned, households choose between 11 combinations of 6 different crop types. Decisions are constrained by land, labour, subsistence, input and knowledge requirements for each of the different crops. If the requirements are met, the household goes on to allocate land accordingly. If labour requirements aren't met, households can attempt to seek labour from their social network, otherwise the land is left to fallow.

Long-term land allocation decisions are adjusted each month based upon agricultural labour availability. The monthly labour requirements are first calculated. The area allocated to a given crop is multiplied by its corresponding labour requirements per hectare. This is then summed. If labour availability for farming meets the requirements, households distribute labour according to crop priority. Should there be any surplus labour households can allocate crops to fallow patches. If households have no fallow patches they can consider clearing forest patches instead or offer labour to members of their social network. If labour availability for farming doesn't meet the requirements, households can attempt to seek labour from their social network.

Conduct livelihood activities. Households conduct a number of activities in addition to farming. These include: collecting firewood and water, tending to livestock and carrying out casual agricultural labour (ganyu). In addition, households may forage for 'wild' foods and carry out non-agricultural work. Decisions surrounding the extraction of firewood and water are simulated using a modified version of a common pool resources model described by Agrawal *et al*. (2013). Time spent upon both casual labour and non-agricultural work is multiplied by an hourly wage estimated from household survey data. Output in calories for time spent foraging for 'wild' foods on the other hand, is drawn from a distribution consistent with the IHS3 survey data. Time spent tending to livestock is also multiplied by an expected hourly output of meat, eggs, milk and manure in kg. A further procedure then determines the proportions of outputs that are eaten, sold, or lost. Proportions are based upon household type with data taken from the IHS3. It is assumed that all stored outputs are eaten within the monthly time step.

Harvest crops. Each month a procedure checks the crop types that are due to be harvested. Expected yield is then calculated using crop specific regression equations taking into account labour, inputs and rainfall that have accumulated during past time steps. Development of regression equations involved three stages: i) extracting and cleaning plot variables from the sampled IHS3 data set; ii) developing a linear regression model to predict yield in terms of labour, inputs and rainfall for each of the 11 cropping patterns and iii) validating the model using a separate validation data set. When yield was predicted based on annual rainfall (mm), application of inorganic fertiliser (kg/ha), organic fertiliser (kg/ha) and labour (hrs/ha) were all significant predictors. The overall model fit was highly significant ($F_{1,3970}$) = 70, $p < 2 \times 10^{-18}$) with an R-squared value of 19.5%. In line with livestock activities described above, a further harvest procedure determines the proportions of crop outputs that are eaten, sold, or lost. It is assumed that all stored outputs are eaten within a monthly time-step. Again, proportions are based upon household type with data taken from the IHS3.

Evaluate food security status. A procedure first calculates potential food-availability from self-production and the market. The total number of calories from crops, livestock products and forage is quantified. A sub-procedure then calculates the actual amount of calories that a household can access from self-production and the market. This takes into account crop losses and inefficient market conditions. Surplus calories are then calculated as the difference between food needs of the household and the total amount of accessible calories. If the surplus variable is greater than zero it is diverted into a calorie-pool that can be donated to members of the household's social network. If surplus is less than zero it is converted into a calorie deficit.

Adopt coping strategies. Households with calorie deficits may adopt coping strategies including: participation in government-led food-for-work programmes, sale of livestock and borrowing food from the social network. A procedure first determines the amount of calories from government cash-for-work and food-for-work schemes. Participation is calculated based on household type and labour availability. The monetary value of work carried out is drawn from a distribution consistent with survey data. Income is then converted into maize calories using a conversion factor. If households still have a calorie deficit, a further procedure determines the amount of food a household can borrow from their social network. Based upon the theory of generalized reciprocal exchange (Kranton, 1996), households select a neighbour from their social network at random. Calories are taken from the neighbour's calorie-pool and the household's calorie deficit is updated. If the deficit is still greater than zero, the household can select a limited number of additional neighbours (dictated by the variable *n-f-interact*). After this point, If a household still has a calorie deficit, they may consider selling livestock in order to purchase calories. The number of livestock remaining is updated accordingly.

Update food availability, access, utilisation and stability. Food access is adjusted to include calories available from coping strategies. A procedure then evaluates the ability of households to process calories. Techniques from fuzzy logic (Zadeh, 1965; Zadeh, 1996) are employed to determine overall 'processability' using a simple fuzzy inference system. Water, fuel and health are set to 'good', 'moderate' and 'poor' on the basis of meeting basic needs or not. Simple rules are then used to label processability, 'good', 'moderate' or 'poor' before being de-fuzzified to give a value between 0 and 100. Food utilisation can then be calculated by multiplying potential calories by the processability value. Whether food needs of the household have been met is then determined and stocks of water and firewood are updated.

In order to quantify food stability, measures of production stability, market stability and political stability are first calculated. This involves calculating the coefficient of variation (CV) for a number of indicators. Production stability is evaluated based on the CV of monthly crop production. Market stability considers variation in annual grain price. Political stability is the average CV of the proportion of households with i) access to inputs and ii) access to payment for work schemes. Lower CV values suggest greater stability of output (and vice versa). A simple fuzzy inference system is then employed to give a value of food stability between 0 and 100, with 0 being the lowest and 100 the highest. The overall food security status of households is then determined using a further fuzzy inference system. This time taking into account food availability, access, utilization and stability, each household returns a food security value between 0 and 100, with 0 being lowest and 100 highest.

Adjust household type. At the end of the agricultural season, a household may adjust its 'type' to suit the prevailing livelihood strategy. This is based upon the proportion of time that was spent by the household upon farming, agricultural labour and non-agricultural activities over the past year. In order to create fixed thresholds with which to categorise households, a classification and regression tree (CART) was developed. Results from the initial cluster analysis performed by Dobbie *et al*. (under review) were used to construct the classification tree (Fig. 3.8). Simple 'IF ELSE' rules were then developed to determine the type of a household at the end of each simulated agricultural season.

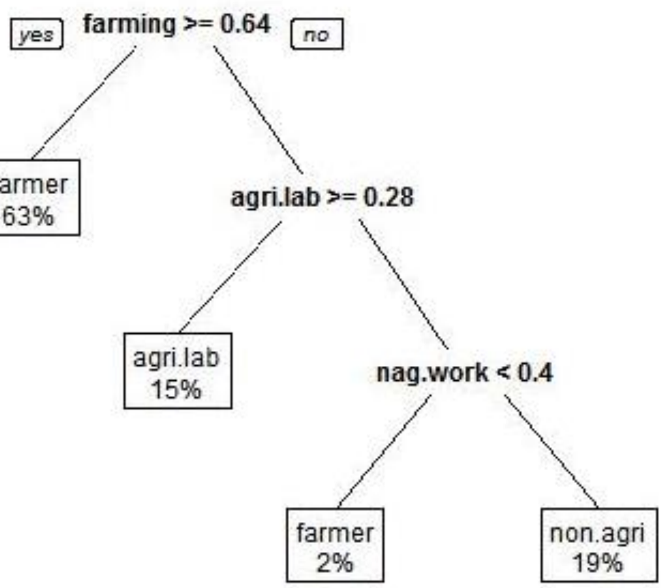

Figure 3.8: Classification and regression tree (CART) to distinguish between farmers, agricultural labourers and non-agricultural workers based upon the proportion of time spent on different livelihood activities.

Over time, the dynamic nature of livelihood strategies causes households to follow one of four trajectories: i) hanging in ii) stepping up iii) stepping out or iv) falling down (Dorward *et al.*, 2009; Falconnier *et al.*, 2015). Under this framework, previous results described by Dobbie *et al*. (in review) imply that agricultural labourers may step out to become either farmers or non-agricultural labourers. Farmers on the other hand may step out to become non-agricultural workers or fall down to become agricultural labourers, whilst non-agricultural workers may only fall down to become either farmers or agricultural labourers (Fig. 3.4).

Implementation

The model was implemented within Netlogo 5.2.1 (Wilensky, 1990). Three model extensions have been used: array, network (Wilensky, 1990) and NLfuzzy (Machálek *et al.*, 2013). Further details surrounding model initialisation and input data are given in Appendix B.

3.3.4 Uncertainty Analysis

Once constructed, we employed a number of techniques to explore model uncertainty. Firstly, attempts were made to investigate the effect of uncertainty that arises through stochasticity, which is inherent to both real-world and simulated systems. The number of simulation samples required to mitigate stochastic effects can be explored using consistency analysis (Alden *et al*., 2013). Consistency analysis contrasts distributions of simulation responses, which are generated using the same set of parameter values, but different sample sizes (Alden *et al*., 2013). Larger sample sizes will mitigate the effect of simulation stochasticity on results, as increasingly identical distributions are produced (Alden *et al*., 2013). However, large numbers of replicate runs come at a computational cost and so it is important to identify the smallest number of model runs that are required to ensure consistent outcomes.

To conduct the consistency analysis, distributions of simulation outputs resulting from model runs using identical parameter values were compared using Simulation Parameter Analysis R Toolkit Application (SPARTAN) (Alden *et al.*, 2013). The number of runs required to ensure statistical consistency of outcomes was determined by altering the number of replicates within each distribution. In this case, a total of 20 distributions were used and sample sizes of 5, 50, 100, 150 and 200 model runs were analysed. For a sample size of 5, each of the 20 distributions contained the results of 5 runs, etc. A distribution of median model outcomes responses for each simulation run was then generated for each of the 20 subsets. Distributions 2 to 20 were compared with the first distribution using the Vargha-Delaney A-Test. This is a non-parametric effect magnitude test that provides a statistical measure of the difference between two distributions (Vargha and Delaney, 2000). Samples from two distributions were contrasted and the probability that a randomly selected sample from one distribution would be larger than a randomly selected sample from the other was calculated. In agreement with Vargha and Delaney (2000) A-Test scores above 0.71 or below 0.29 indicated a significant difference between distributions and 0.5 indicated no difference. A sample size was deemed suitable when no statistical difference was found between the first set of A-Test scores and the remaining 19 distributions.

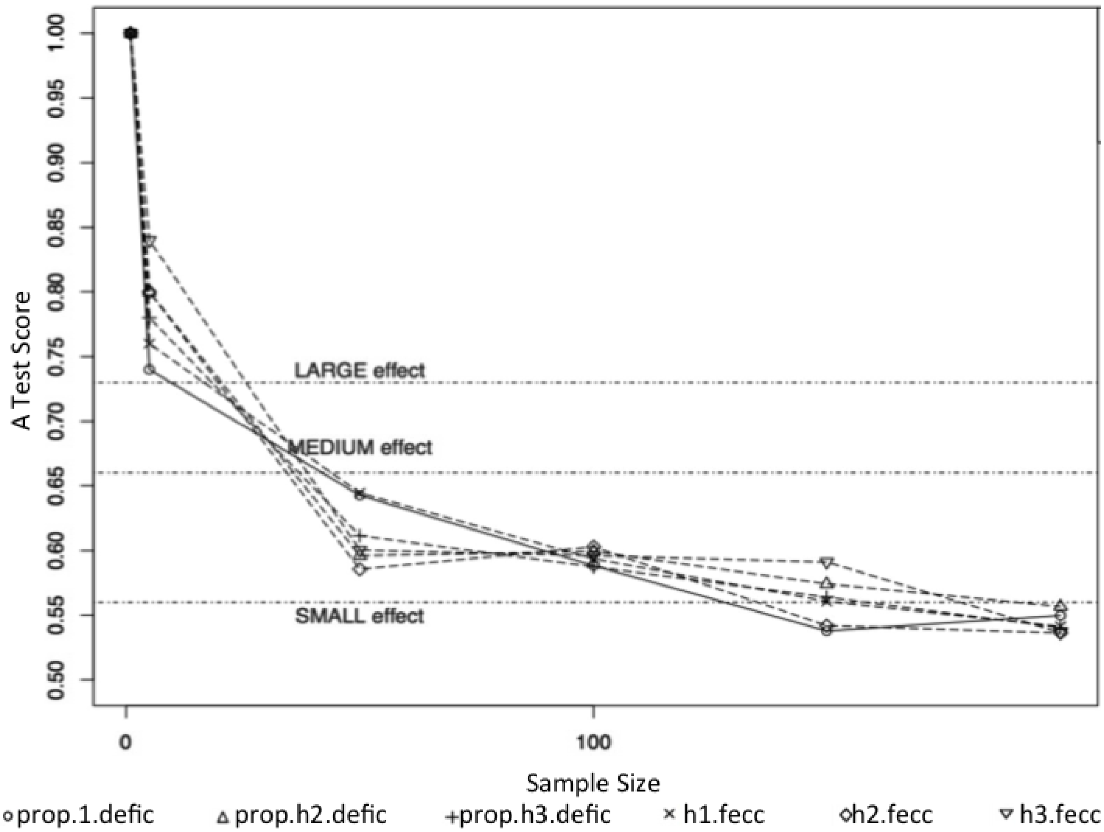

Figure 3.9: Maximum A-Test score for each simulation response over the 20 result sets for sample sizes: 1, 5, 50, 100, 150 and 200. Measures include the proportion of food energy deficient households (prop.defic) and the daily food energy consumption per capita (fecc), disaggregated for farmers (h1), agricultural labourers (h2) and non-agricultural workers (h3). The effect of stochasticity upon simulation responses are shown by horizontal lines and described as small, medium or large dependent upon A-Test scores (see accompanying text).

The maximum A-Test score for each simulation outcome over the 20 resulting distributions is shown for all sample sizes analysed (Fig. 3.9). Attention was paid to outcomes in the form of daily food energy consumption per capita (kcal per capita per day) and the proportion of calorie deficient households (%). Results are disaggregated based upon household type, namely farmers (h1), agricultural labourers (h2) and non-agricultural workers (h3). Results from the analysis implied that reducing the effect of stochastic uncertainty on simulation results to less than ‘small’ requires at least 200 model runs.

Table 3.1: Description of parameters tested for robustness

Parameter	Description	Baseline Value	[min, increment, max]
n-l-interact	The number of times a household can call upon its social network for labour in a given month.	4	[2,2,20]
n-f-interact	The number of times a household can call upon its social network for food in a given month.	2	[2,2,20]
m-efficiency	Adjusts the amount gained from sales and/ or purchases of livestock and crops to take into account the efficiency of the market.	0.8	[0.2,0.2,1]
nag-avail	Adjusts the amount gained from time allocated to non-agricultural work to take into account the availability of work.	0.8	[0.2,0.2,1]
multiplier	Provides a limit to the amount of calories an individual is able to consume.	1.6	[1,0.2,2]

A further technique was used to investigate the impact of uncertainty surrounding simulation parameters. According to Spartan *et al*. (2013), any real-world simulation will feature parameters for which values are fully or partially unknown. When interpreting results it is important to take into account whether a simulation is highly sensitive to such parameter estimations or not (Spartan *et al.*, 2013). It is possible that results may be artefacts of parameterisation rather than representations of the real world system of interest (Spartan *et al.*, 2013).

Five simulation parameters for which values are currently unknown were analysed for parameter robustness. These included: the number of times a household can call upon its social network for

i) labour and ii) food in a given month, *n-l-interact* and *n-f-interact*, respectively; as well as the efficiency of markets *m-efficiency*, the availability of non-agricultural work *nag-avail* and *multiplier*, a value that limits the amount of calories individuals can consume in a given month. A local sensitivity analysis was conducted, perturbing each parameter independently of all others, which were maintained at baseline values (Table 3.1). Simulation outcomes under perturbed conditions could then be compared using the Vargha-Delaney A-Test described above (Vargha & Delaney 2000). If altering the value of a particular parameter from a baseline or calibrated value had a significant effect on simulator output, the simulation was deemed highly sensitive to that parameter and caution applied when interpreting the result and establishing a value for that parameter.

A significant effect on simulation responses was uncovered for four of the parameters, including: *n-f-interact*, *m-efficiency*, *nag-avail* and *multiplier* (S1-S5: Fig. 3.14-Fig. 3.18). The number of times a household can draw upon its social network for labour, *n-l-interact* had little effect on simulation outcomes, however.

3.3.5 Model Validation

The model was validated using both qualitative and quantitative approaches during different stages of the design and implementation process. A role-playing game was devised to test the behavioural rules underpinning key decision-based procedures within the ABM. A total of 14 experts associated with the ASSETS project took part in a two-day workshop convened in January 2015.

Participants took on the role of one of the three household types: farmers, agricultural labourers or non-agricultural workers. Each 'household' followed decision tree rules to allocate land to cropping strategies, interact with social networks to borrow/ donate labour or food and update financial capital. Following the exercise, a discussion was facilitated to evaluate the behavioural rules of households and determine whether alterations to the model code were required.

The use of role-playing games to construct and validate the behavioural rules of agents has been widely documented for empirical ABMs (Bosquet *et* al., 2002; Guyot and Honiden, 2006; Joffre *et al*., 2015). Expert knowledge can be used to explore methodological uncertainty surrounding the structure of the simulation tool and the mechanisms underpinning it (Moss, 2008). In this study, by taking a participatory approach to validation we were able to engage experts from a range of domains including the social sciences, natural sciences and economics. A number of suggested improvements resulted from the workshop, including:

- To stagger land allocation decisions of households to limit the number of farm plots left to fallow.
- To allow households to allocate crops to larger farmer patches at first, rather than at random.
- To include the possibility to rent land.
- To improve interactions between households by refining the scheduling of food sharing and money borrowing within the social network.

These points were addressed throughout the iterative development process of the ABM. The amended simulation tool was then validated quantitatively. To do this, the generic village-level model was parameterised using case study data (See Section 3.2.1.2) and run for 12 time-steps from May 2013 to June 2014, corresponding to the data collection time-frame (see 3.2.1.2). Mean results from 200 model simulations were then compared with the empirical data, focusing on outcomes in the form of land use and food security at the household level (Fig. 3.10).

Figure 3.10: Observed and predicted values for A) the number of months a household was food insecure over the past 12 months; B) the proportion of land a household allocated to grain crops during the 2013-14 farming season. Predicted results are based upon average values for 200 replicate runs. RMSE: root mean squared error.

Simulation results overestimated the number of months households are food insecure (Fig. 3.10A). The root mean squared error (RMSE) was high at 5.4 months. While it would be possible to tune the model in order that this RMSE is reduced, care needs to be exercised in interpreting the empirical data that the model is being compared with. The household food security data was compiled using an indicator based upon an individual's perception of household food security.

Jones *et al*. (2013) recognise experience-based measures of food security may result in a broad range of response bias. Changing environmental conditions may cause respondents to alter internal standards of food security, resulting in 'response drift' (Maes *et al*., 2009). One individual's perception of food security may not be representative of the household and it may be difficult to ensure the definition of recall periods across respondents remains consistent *(*Jones *et al.*, 2013). Further research should use additional survey instruments such as food diaries or household consumption and expenditure surveys to estimate food consumption and the actual food security status of households. This will enable further model fine-tuning and validation.

Model results for land allocation decisions were much closer to empirical data, although the number of single crop systems was significantly lower (Fig. 3.10B). The percentage area of land given to grain crops was predicted with a RMSE of 29.9%. As with household food security data, land allocation data should be viewed with caution as measures of land allocation were based upon household recall and best guesses rather than empirical measurement.

In this case a conscious decision was made not to fine tune parameters based on the case study data as this data had not been collected with the intention of validating the model. As a result, the indicators collected were not ideal for testing model outcomes. According to Epstein and Forber (2012) using macroscopic data to adjust micro-level simulation parameters risks overfitting the simulation to the data. Tweaking parameters may result in a simulation that accommodates the data at the expense of misrepresenting micro-level interactions, which generate the behaviour of interest (Epstein and Forber, 2012). Further work is therefore required to collect and analyse data specifically for model validation purposes.

3.3.6 Scenarios

The model was run from June 2010 to May 2050. Over time, changes to climate, markets and population were projected. Climate variability was represented by annual rainfall. At the beginning of each model year, a value is drawn from a list of rainfall data. This list was generated using MarkSim, a third-order Markov rainfall generator that can be employed as a Global Climate Model downscaler (Jones and Thornton, 2013). Daily rainfall projections for Malawi were generated from 2010 to 2050. This was based upon the average output of 17 GCMs using the RCP2.6 scenario, as defined by the IPCC (Van Vuuren *et al*., 2011). Daily values were then aggregated to give an estimate of annual rainfall.

Village-level population growth was approximated using rural population projections from the 2014 revision of world urbanisation prospects (UN, 2015c)**.** As projections consider the number of individuals only, the growth in household numbers at the village level had to be estimated. This was achieved using the simple equation:

$$hh = rpop * prop / hhsize \qquad (3.2)$$

where *hh* is the number of households, *rpop* are the rural population projections (UN, 2015c), *prop* is the proportion of rural individuals living in Southern Malawi and *hh-size* is the average size of households (based on census data for 1987, 1988 and 2008). In order to simulate population growth, at the end of each model year, the number of new households to be created is read from a list. Households and individuals are created and initialised accordingly, drawing upon data from IHS3. In order to allocate patches, each new household asks a member of its social network to spare their smallest patch of fallow land. Patches may also be split. This reflects the matrilineal nature of customary land tenure in Malawi (Takane, 2008).

The local market prices for 11 food categories are provided as input to the agent-based model at initialisation. The model stores the annual market price of these commodities starting at 2010 for the following 40 years. The market value of crops and livestock products such as milk, eggs and meat play an important role within the model. Changes over time are simulated using two well established global models, AGLINK-*COSIMO* (OECD and FAO, 2015)and GCAM4.0 (Kyle *et al*., 2011; Capellán-pérez *et al*., 2014).

3.4 Results

The four pillars of food security were quantified for each household and are summarized at the village level for farmers, agricultural labourers and non-agricultural workers (Fig. 3.11). Overall, non-agricultural workers tend to have greater food availability, access, utilisation and stability when compared with farmers and agricultural labourers. Taking into account population growth, rainfall variability and market projections, the availability and access dimensions of food security remain stable between 2010 and 2050. Large declines in utilisation and stability of food however, are anticipated for all households by 2050. Such reductions are the result of increased exploitation of the natural resource base over time.

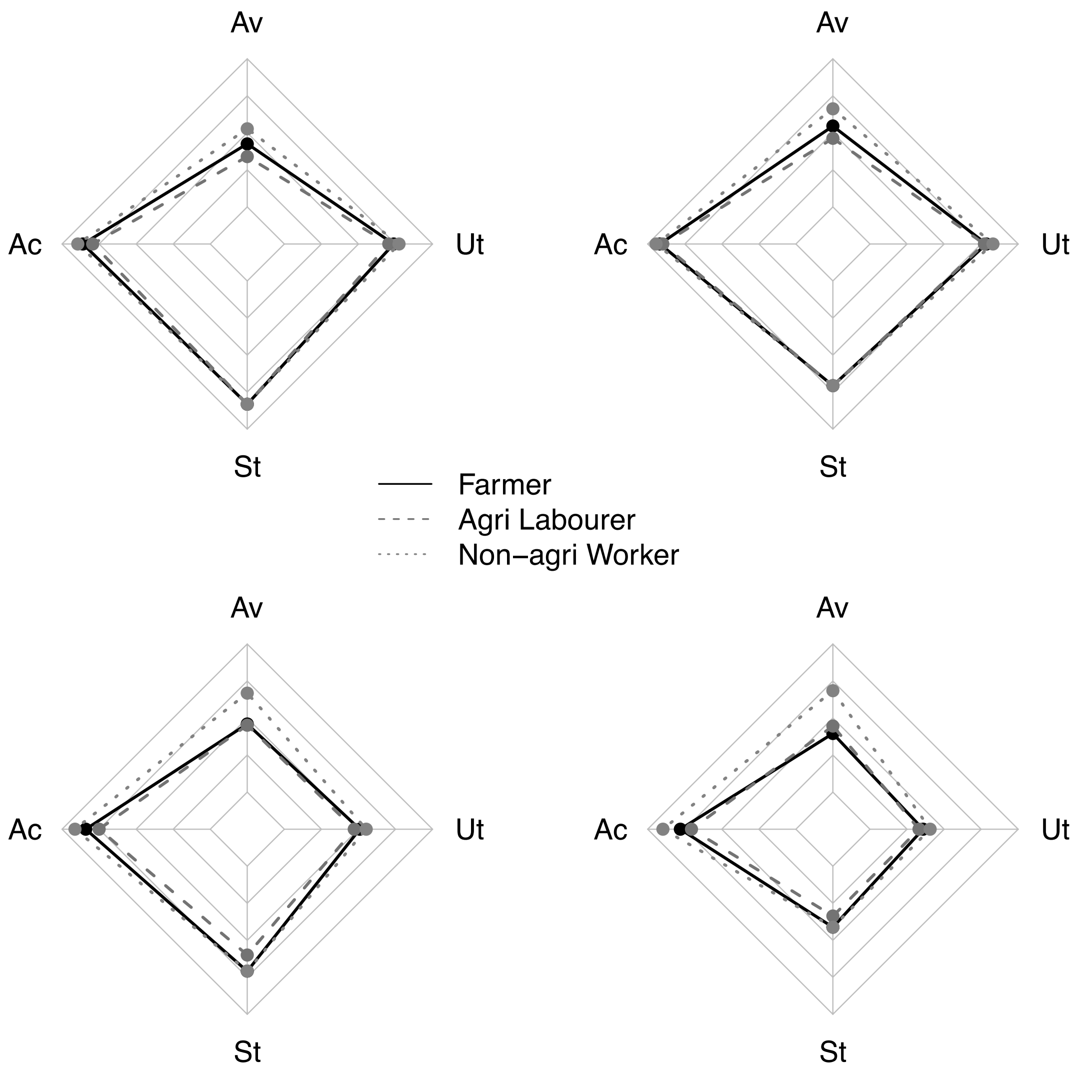

Figure 3.11: Household food security status over time Av: Availability; Ac: Access; Ut: Utilisation; St: Stability. Simulation outputs take into account population growth, rainfall variability and market variability. Mean results for 200 replicate runs are given for farmers, agricultural labourers and non-agricultural workers.

Indeed, the ability of households to utilise food is dependent upon access to sufficient amounts of water and fuel as well as a household's health and wellbeing. Model outputs suggest that the proportion of household water needs met could decline from 92% in 2010 to 44% in 2050. This is due to increased demand for water as the population increases. The stability of food is an emergent property of market, political and production stability. Under the current scenario, although political stability remains fixed throughout, market prices are assumed to exhibit annual variation. The price of grains per kg is projected to increase from 0.3 USD in 2015, to 0.7 USD by 2050.

Crop production is assumed to be affected by the availability of land and labour as well as rainfall. Simulation outputs show large variation in the production of grains over time (Fig. 3.12A). Non-agricultural workers are projected to experience a sharp decline in grain output between 2011 and 2030. During this period the mean quantity of grain produced falls from 209.3kg to 104.8kg. Agricultural labourers also experience a severe drop in grain output, which fluctuates between 38.3kg and 69.4kg from 2012 onwards. Average annual grain output for farmers on the other hand, increases from 232.1kg in 2011 to over 300kg by 2050. Results for grain output reflect changes in the proportion of households with access to land (Fig. 3.12B), highlighting the importance of land tenure to food security outcomes over time.

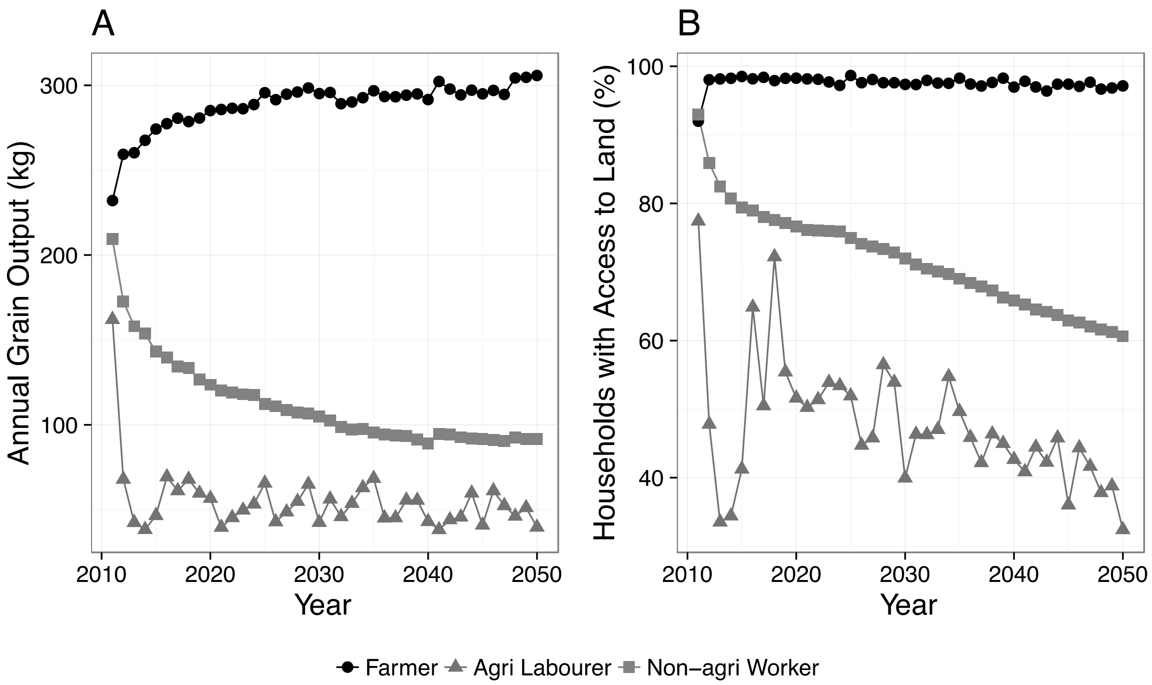

Figure 3.12: A) Mean annual grain output in kg; B) Mean proportion of households with access to farmland. Results are average values for 200 replicate runs.

The shift in household trajectories (as outlined in Fig. 3.4) over time can also be visualised (Fig. 3.12). Sustainable livelihoods are expected to demonstrate resilience to shocks and stresses over time. The number of households ‘falling-down’ into a less food secure category is projected to be minimal at less than 1% overall (Fig. 3.13A). Farmers tend to ‘hang-in’ or ‘step-up’ within their category rather than ‘stepping-out’ to become non-agricultural workers (Fig. 3.13B). Agricultural labourers, on the other hand, appear the least stable. The proportion of households ‘hanging-in’ fluctuates over time. Only a small number of agricultural labourers ‘step-up’, instead the vast majority ‘step-out’ to become farmers or non-agricultural workers (Fig. 3.13C). Interestingly, between 2010 and 2050, none of the non-agricultural workers ‘fall-down’. However, the proportion of such households ‘stepping-up’ declines from almost 60% in 2010 to just 32% in 2050 (Fig. 3.13D).

The dynamic nature of household livelihoods can be linked to trends in land access (Fig. 3.12B). Over time increasing numbers of agricultural labourers ‘step-out’ to become non-agricultural workers. These households tend to own less land and the ability to acquire new land is constrained by the area of fallow and forest remaining. As the population grows between 2011 and 2050, the proportion of households with access to land declines by approximately 20%.

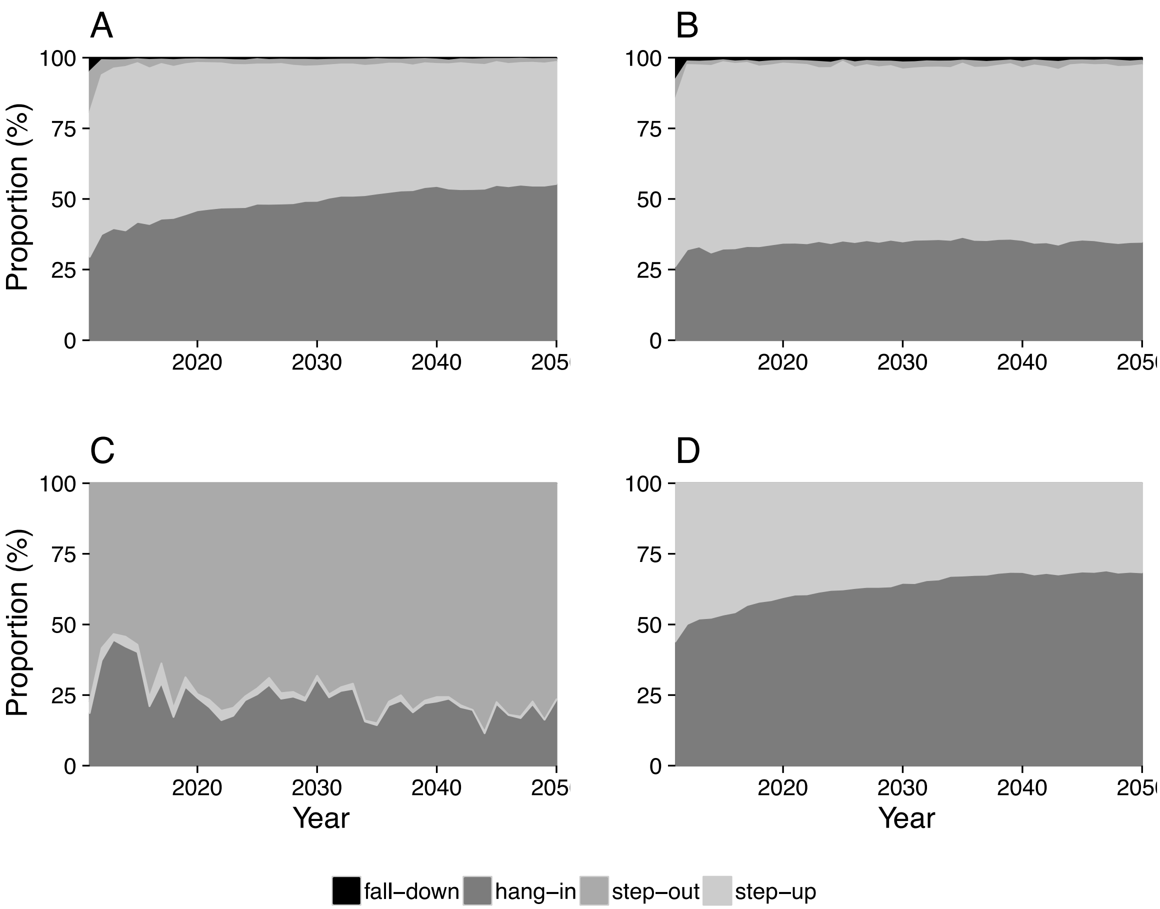

Figure 3.13: Household trajectories A) Village; B) Farmer; C) Agri Labourer; D) Non-agri Worker. Results are average values for 200 replicate runs.

3.5 Discussion

3.5.1 Social-ecological Interactions and the Emergence of Community Food Security

The ABM presented here provides a tool to assess how interactions between households and the environment may lead to the emergence of community level food security. Within the context of rural Malawi, non-agricultural workers tend to be the most food secure when compared with farmers and agricultural labourers. Community food security, however, can only exist when all residents obtain a safe, culturally acceptable, and nutritionally adequate diet (Hamm and Bellows, 2003). Efforts must therefore be made to target policies and development programs towards improving the sustainability of livelihoods based upon farming and agricultural labour.

Knowledge of livelihood strategies and food security outcomes at the community level generated by this research may help build shared understanding and capacity for action. Practice of community food security is in its infancy, however interesting parallels can be made to the African Millennium Villages. Since the year 2000, a total of 78 Millennium Villages have been initiated in 12 sites in 10 African countries (Sanchez *et al*., 2007). Science-based research and interventions at the community level are suggested to have enabled food energy requirements of households to be met (Sanchez *et al*., 2007).

Complementing existing national and district-level conceptualisations of food security with village level perspectives could address scale mismatches present within social-ecological systems. National policies and regulations that are effective over larger geographical scales can have unintentional consequences at finer scales in which local conditions may differ significantly from the mean (Cumming *et al*., 2006). By taking a bottom-up approach and exploring how social-ecological interactions lead to the emergence of community food security, it is possible to take heterogeneity into account and develop context specific solutions.

In order to be useful to decision makers, model outputs must be credible. A key strength of our methodological approach is the ability to explore model uncertainty and validity. Use of SPARTAN enabled two techniques to be operationalised, namely consistency analysis and parameter robustness. Both qualitative and quantitative approaches were also used to validate the model. Comparison of simulation outputs with empirical data uncovered inconsistencies between food security indicators. The model consistently overestimated the number of months that households were food insecure. However, this may be explained by a disparity between actual and perceived food security status as reported by the model and the survey data, respectively. Additional data sets should be used to verify and validate the model further. Combining quantitative validation with qualitative efforts has proved beneficial. Promoting dialogue with stakeholders during role-playing exercises ensures that the model fits not only the data, but also its purpose.

3.5.2 The impact of rainfall variability and population growth on food security

By quantifying food availability, access, utilisation and stability, the model enables the impact of exogenous factors on the multidimensional nature of food security to be explored. Rainfall variability and population growth for instance were linked to declines in food utilisation and stability over time.

However, a number of simplifications were made when modelling population dynamics. Population growth for example, was represented by the addition of households at the end of the simulated year. Existing households remained with the same number and age of individuals as before. This means that the current model does not fully capture age structure, fertility, mortality and migration.

Despite model simplifications, simulation outputs were found to correspond closely with observations and theories documented within the literature. Within Malawi, the proportion of young people is set to increase over time (UN, 2015c). As the number of young adults rises, the inheritance of land, long considered a birth right of rural individuals, will become ever more problematic (Jayne *et al*., 2014). In the simulation, population growth was negatively correlated with land access: as the number of households increased from 116 in 2010 to 263 in 2050, the proportion of households with access to land declined from 90.3% to 74.6%.

According to Jayne *et al.* (2014), behavioural responses of households to land scarcity can be divided into five main trajectories: i) intensification of land use; ii) shifting labour to rural non-farm activities; iii) migration to other rural areas; iv) migration to urban areas; and v) reduction in fertility rates. The simulation was able to reproduce the first two trajectories. Population growth was met with a reduction in the area of land left to fallow. Within Malawi this is recognised as a common repercussion of land intensification (Headey and Jayne, 2014). Regarding shifting labour patterns, model outputs show the proportion of non-agricultural workers increased from 24% in 2010 to 61% in 2050. Such findings are supported by a recent study which found population density had a significant effect upon off-farm income per capita (Ricker-Gilbert *et al*., 2014). Analysis of panel data by Christiaensen and Todo (2014) also uncovered a link between shifting to off-farm activities and poverty reduction.

The current model does not take into account migration and fertility rates, due to poor data availability. Regarding migration, both Jayne *et al.* (2014) and Ricker-Gilbert *et al.* (2014) found little evidence of increased migration under greater population density. Resource constraints, poor public and education services, insufficient road infrastructure and market access, coupled with cultural differences seem to discourage the migration of households from Southern to Northern Malawi in order to obtain arable land (Ricker-Gilbert *et al.*, 2014). Urban migration in response to increased population growth is contested within the literature. Studies by Englund (2002) and Potts (2006) suggest rural migrants rarely settle in urban areas, however other studies suggest that Malawi has a very high urbanisation rate and highlight the link with climate change (GoM, 2013; Suckall *et al*., 2015).

The response of fertility rates is also uncertain for Malawi. A recent study found that, whilst achieved fertility rates did not differ significantly between high density countries such as Benin, Ethiopia and Malawi, and low density countries (e.g. Niger, Tanzania and Zambia), the fertility rates desired by African women decrease with increasing population density (Headey and Jayne, 2014). Women with similar levels of education and agricultural income desired roughly 1.5 fewer children in a higher density country such as Rwanda (420 people per km^2), when compared with a lower density country such as Tanzania (90 people per km^2). Future work could use the model to further investigate the effect of household demographics upon food security.

Climate was characterised within the model by annual rainfall. In addition to changes in rainfall frequency and intensity, climate change in sub-Saharan Africa is anticipated to cause temperature increases, along with more frequent shocks and stresses in the form of droughts and floods (McSweeney *et al*., 2008). This will shorten growing seasons, reduce the area of land suitable for agriculture and lead to declines in agricultural yield (Wolfram and David, 2010; Vizy *et al*., 2015; Dube *et al*., 2016). Currently such factors are out of the scope of the model as yield is calculated using regression equations, which take into account the accumulation of labour, fertiliser and rainfall. However, there is potential for incorporating additional climatic variables to better explore the impact of climate change upon community food security.

3.5.3 The Impact of Rainfall Variability and Population Growth on Livelihood Trajectories

In its current form, the model also provides a means to trace household trajectories. In this context, non-agricultural workers were the most resilient to shocks and stresses over time. None of the non-agricultural workers were found to 'fall-down' into less food secure livelihood strategies. Despite this, the ability of such households to 'step-up' activities did decline by 2050, with 68.4% of non-agricultural workers opting to 'hang-in'. Farmers were the most likely to 'fall-down' and adopt a less food secure livelihood strategy when compared with other households, however the proportion was low with a mean value of just 1.4% from 2011 to 2050.

Interestingly, model outcomes reflect empirical findings described by Falconnier *et al.* (2015) for Southern Mali. Here, between 1994 and 2010, 70% of households chose to 'hang-in'. A number of technical options were proposed by the authors to avoid stagnation of the agricultural sector and promote trajectories that 'step-up' over time. These included increasing access to farm equipment, promoting mixed cropping strategies with legumes and the intensification of milk production (Falconnier *et al*., 2015). Within Malawi, the ability of non-agricultural workers to step-up, may also be promoted by improved access to credit, better infrastructure and more employment opportunities (Swaminathan *et al*., 2010; Castaing Gachassin *et al*., 2015). By following household trajectories, the model provides a systemic view that addresses the dynamics of agri-food systems within Malawi. According to Thompson and Scoones (2009) by understanding critical feedbacks across multiple scales, effective responses to social-ecological interactions can be designed.

In addition to exogenous factors such as rainfall and population growth, the agent-based model described here can provide a virtual environment through which different policies and development narratives could be explored. For instance, the potential of land tenure reforms (Holden and Otsuka, 2014) and the development of land rental markets (Chamberlin and Ricker-Gilbert, 2013) to increase efficiency and equity could be investigated. The ability of sustainable agricultural intensification to increase food production and reduce negative environmental impacts (Pretty, 2008) through agroforestry, conservation agriculture, integrated pest management and aquaculture (Pretty *et al*., 2011) could also be evaluated. In addition, the role of social security policies, such as conditional cash transfers and school feeding programmes, to alleviate food insecurity of the most vulnerable community members (Devereux, 2016) could be considered.

The approach described here may also be applied to other case studies. Within Sub Saharan Africa for instance, the Living Standards Measurement Study has aided the design and implementation of household surveys within a number of countries (Malawi, Burkina Faso, Ethiopia, Mali, Niger, Nigeria, Tanzania and Uganda) (Grosh and Glewwe, 1998). The data collected in each project country is publicly available. Using our approach, such district data sets could be supplemented with village field studies to construct agent-based models of community food security within a wide range of contexts.

3.6 Conclusions

This study provides a methodological approach for the development of an agent-based model to assess community food security. Issues associated with data scarcity were alleviated by using a typology driven approach that enables models to be built using district level data that tends to be richer and more readily available. This can then be supplemented with village level data to tailor policies and development programmes. The model takes into account the multi-dimensional nature of food security. Availability, access, utilisation and stability dimensions are quantified and can be summarized at both the household and community level. The trajectories of households can also be traced over time. The model is validated in a strategic manner, using both quantitative and qualitative approaches to ensure the simulation tool can reproduce real-world data and also be of use to stakeholders. Model uncertainty is tackled to ensure credibility and ensure the model is fit for decision-making purposes. Future work could focus on exploring household demographics further, as well as using the model to investigate different strategies to enhance community food security. Attempts could be made to validate the model against additional data sets as well as consider how assessments of community food security can guide the design and targeting of policy and development programmes in practice. The creation of agent based models represents a potentially powerful tool that communities and stakeholders could use to ensure all community residents obtain a safe, culturally acceptable, nutritionally adequate diet through a sustainable food system that maximizes self-reliance and social justice.

3.7 Supplementary Information

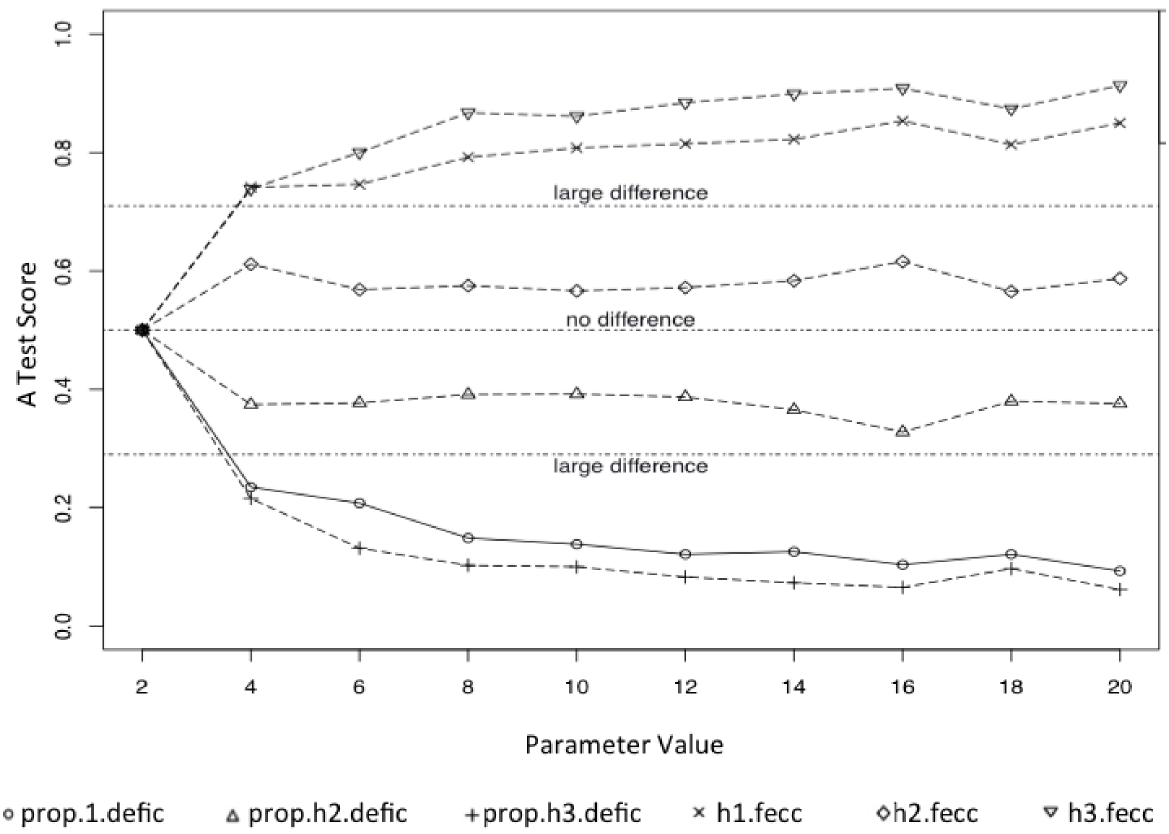

Figure 3.14: A-Test scores when adjusting parameter *n-f-interact*. Measures include the proportion of food energy deficient households (prop.defic) and the daily food energy consumption per capita (fecc), disaggregated for farmers (h1), agricultural labourers (h2) and non-agricultural workers (h3).

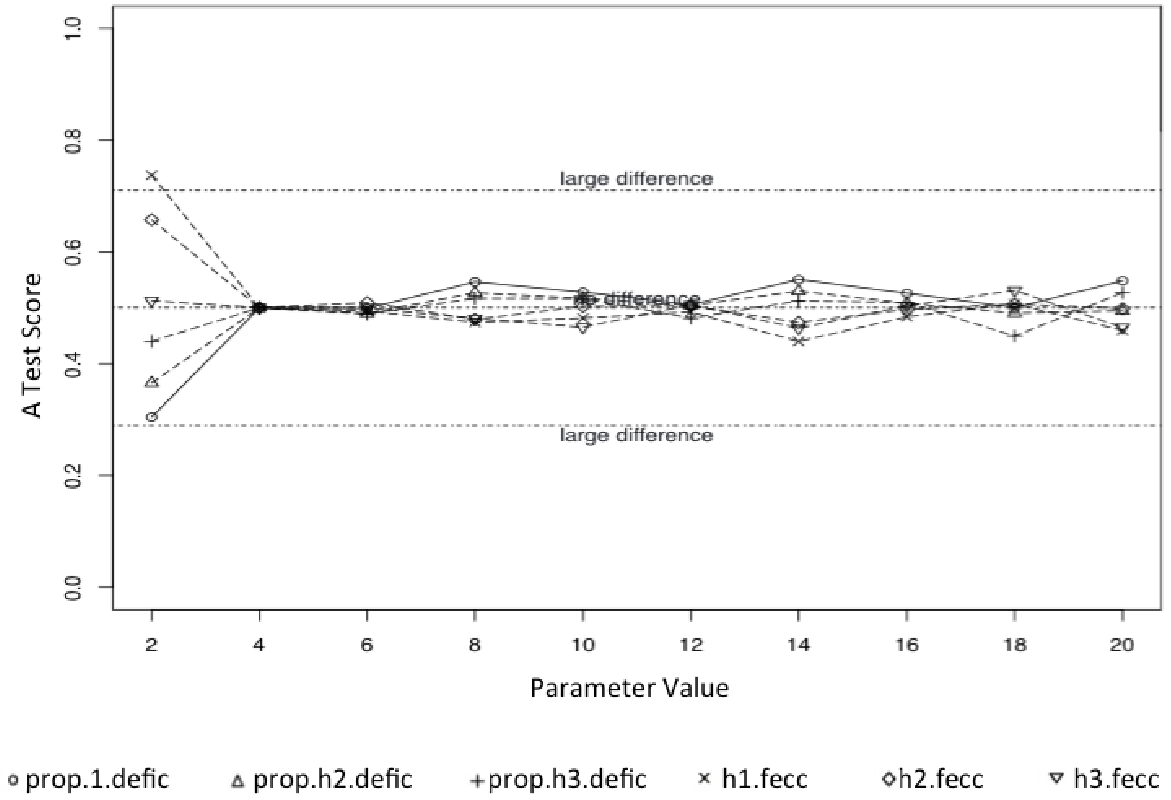

Figure 3.15: A-Test scores when adjusting parameter *n-l-interact*.

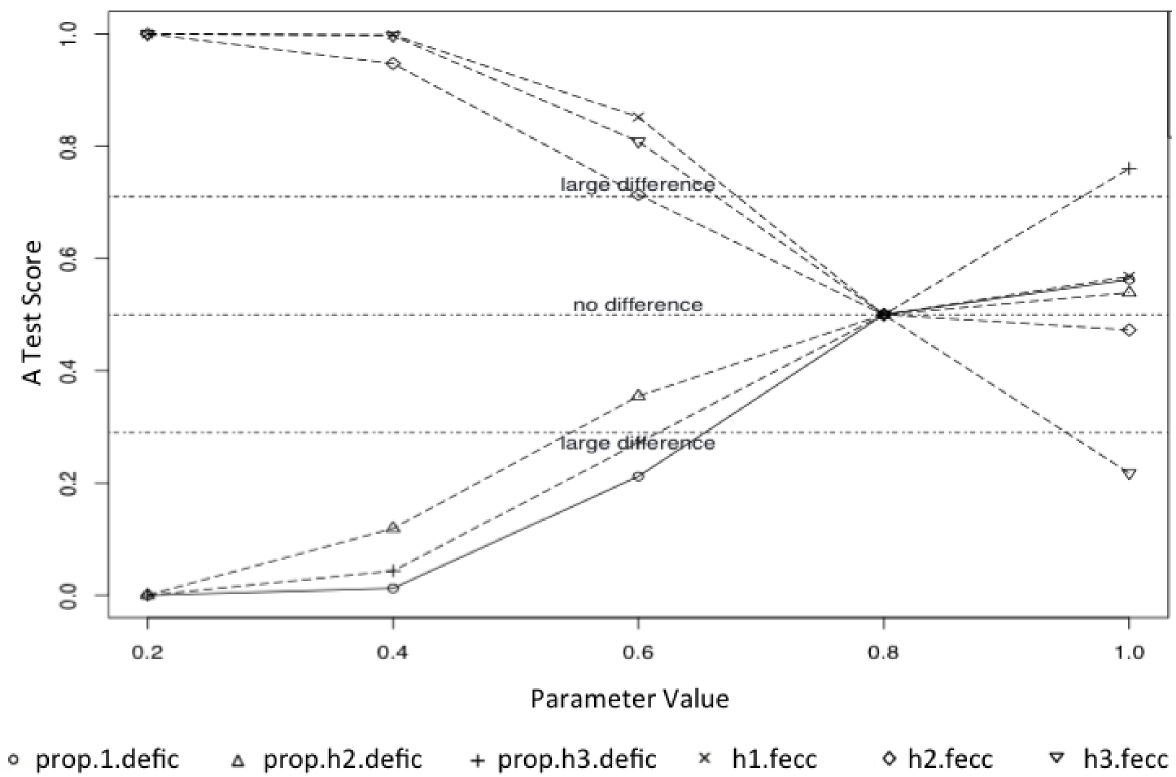

Figure 3.16: A-Test scores when adjusting parameter *m-efficiency*.

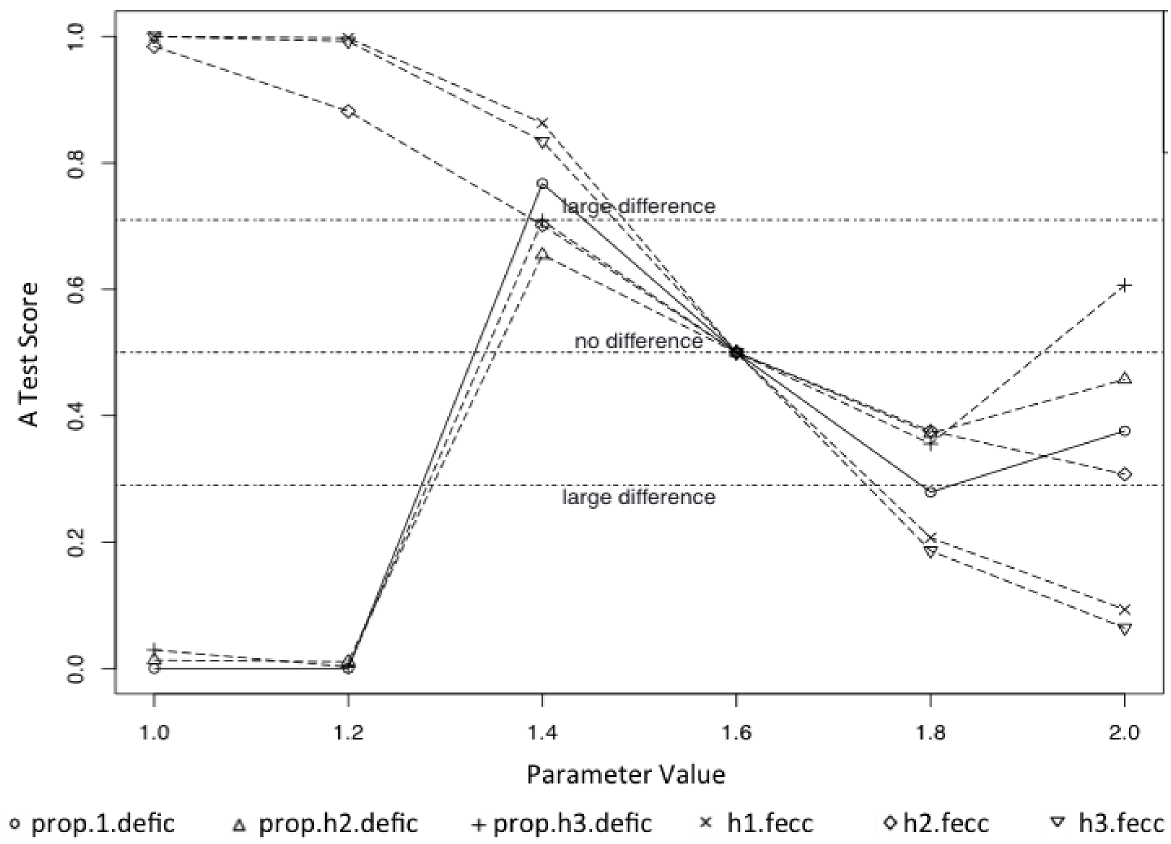

Figure 3.17: A-Test scores when adjusting parameter *nag-avail*.

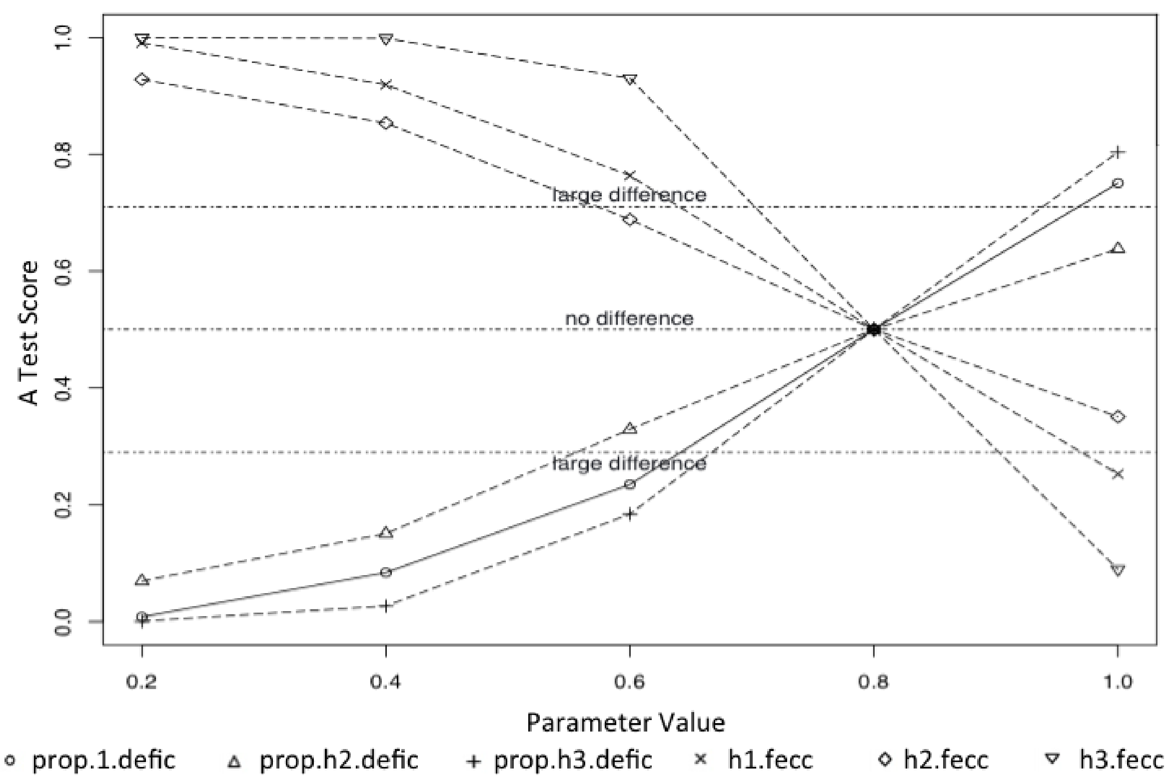

Figure 3.18: A-Test scores when adjusting parameter *multiplier*.

Chapter 4: Navigating Robust and Coherent Pathways to Zero Hunger by 2030: The Use of Exploratory Modelling and Analysis

Abstract

The Sustainable Development Goal to "*end hunger, achieve food security and adequate nutrition for all, and promote sustainable agriculture*" (UN 2015b, p.18), sets an ambitious target for 2030. In order to address food insecurity there is a need for novel tools to help navigate robust and coherent pathways towards zero hunger. We present a data driven approach to investigate different strategies using rural Malawi as a case study. Our approach combined exploratory modelling and analysis with agent-based modelling. This allows for interactions between system components such as households, institutions and the environment to be taken into account. We found that the approach allowed the emergence of diverse food systems and food security outcomes to be investigated and supported the design of robust and coherent policies. Pathways identified were coherent in that they promoted synergies between productivist, nutritionist and social protection strategies in the alleviation of food insecurity. They were also robust to changes in market prices, population growth and rainfall variability over time. Compared with 'business as usual', pathways towards zero hunger were associated with increased access and stability of food. A trade-off was uncovered between food access and utilisation, as increased caloric consumption was met with a rise in the proportion of food energy from staples. Results also provided further support for the adoption of social protection strategies such as cash transfers and payment for work schemes. Future work is needed to assess the practical feasibility of the different pathways.

Key words: food security, sustainable development goals, Malawi, agent-based modelling

4.1 Introduction

The Sustainable Development Goals (SDGs) adopted by the United Nations have set a clear target to end food insecurity by 2030. The aim of Goal 2 is to *"end hunger, achieve food security and adequate nutrition for all, and promote sustainable agriculture"* (UN 2015b, p.18). The target builds upon progress made by the Millennium Development Goals (MDGs), which drew to a close in 2015. In the final progress report for the MDGs, the proportion of undernourished people within developing regions was projected to have fallen from 23.3% in 1990-1992 to 12.9% in 2014-2016, narrowly missing the MDG target to halve hunger by 2015 (UN, 2015).

Closer inspection of country-level progress however, reveals variation behind the aggregates (Fanzo & Pronyk 2011). In China, between 1990 and 2010, the prevalence of undernourishment was reduced by half from 23% to 11% (Fanzo and Pronyk, 2011). Within Brazil and Thailand undernutrition was also eliminated, falling to 7% and 6% by 2013, respectively (Fan *et al*., 2015). Progress within Sub-Saharan Africa however, was muted (FAO *et al*., 2015). In Malawi, the proportion of undernourished people rose from 22% in 2005 to almost 26% in 2013, failing to meet the MDG target of 11.8% (Gondwe, 2014).

The choice of indicators for the MDGs was argued by Fukuda-Parr et al. (2014) to be reductionist. Progress was measured based upon i) the prevalence of underweight children under five years of age ('weight for age indicator') and ii) the proportion of the population below minimum level of dietary energy consumption (UN, 2001). The two indicators fail to recognise the multidimensional nature of food security, which is based upon availability, access, utilisation and stability (FAO, 2009). They focus attention on food supply rather than access and on caloric consumption rather than nutrition (Fukuda-Parr *et al*., 2014). The MDGs have also been criticised for their lack of attention to local agency (Bond, 2006), leading Pimbert (2009) to reject the neo-liberal paradigm for food and agriculture embodied by the MDGs and instead emphasise food sovereignty and community food security. The latter take into account the complex social-ecological contexts in which local food systems are embedded (Pimbert, 2009).

The aim of this chapter is to explore how pathways to zero hunger may be navigated. In order to achieve a future without hunger, over the past few decades, three distinct policy agendas have dominated the food security discourse. These are based upon productivist, nutritionist and social protection strategies, respectively (De Schutter, 2014). For the former, attempts are made to increase the productivity of agri-food systems. This may involve closing the yield gap and improving resource efficiency through innovations such as agroforestry, conservation agriculture, integrated pest management and improved infrastructure and market access (Pretty *et al*., 2011; Pradhan *et al*., 2015).

Nutritionist strategies draw attention to the 'triple burden of malnutrition' (Labadarios, 2005; Pinstrup-Andersen, 2007). Attempts are made to address inadequate food intake, excessive food intake and micro-nutrient deficiencies (Pinstrup-Andersen, 2007). Interventions include fortification of foods, educational campaigns to promote good feeding practices and improved access to clean water and sanitation (Lassi *et al*., 2013; Ruel & Alderman 2013; Ngure *et al*., 2014). Finally, social protection strategies advocate the introduction and preservation of safety nets such as conditional cash transfers and school feeding programmes to alleviate food insecurity (Devereux, 2016).

According to Naylor (2014) solutions based on a silver bullet mentality are destined to fail. Instead, multiple evidence-based approaches will be required to eradicate food insecurity in the coming decades (De Schutter, 2014). Success stories from Brazil, China, Thailand and Vietnam suggest that eliminating hunger by 2030 is possible (Fanzo and Pronyk, 2011; Fan *et al*., 2015; Scherpbier, 2016). However, the strategies employed differ significantly.

In China and Vietnam, for example, productivist strategies were prioritised. The introduction of the Household Responsibility System in China secured land rights, facilitated pro-market reforms and accelerated agricultural growth (Fan *et al*., 2007). Similarly, the Doi Moi reforms in Vietnam promoted land reforms, liberalisation of agricultural marketing and trade, as well as investment in human development (Tran, 2013). In Brazil, attention was given to social protection and nutrition interventions. The Bolsa Família programme combined cash transfers with improved education and healthcare for beneficiaries (Saad-Filho, 2015). Progress made in Thailand however, has been attributed to both productivist and social protection strategies (Fan *et al*., 2015).

Grand challenges such as food security typically arise in systems characterised by a multiplicity of components that interact using a variety of mechanisms which can only be partly observed (Hammond and Dubé, 2012). The term dynamic complexity refers to the sometimes surprising and counter-intuitive behaviour that can arise within systems as a result of non-linearity, interactions and feedback loops between system components (May and Oster, 2011). This poses problems for the management of systems, as changes in one process may be resisted (or even reversed) by adaptive responses elsewhere in the system. Likewise, synergies and feedbacks between components which could have advantageous outcomes when harnessed by policy makers might remain unnoticed (Hammond and Dubé, 2012). To be effective, policies must be coherent. The impact of policies and development programmes must not undermine food insecurity (Brooks, 2014). Furthermore, coordination of policies across sectors must be mutually supportive as opposed to off-setting (Brooks, 2014).

With this in mind, there is a need for novel tools to help navigate robust and coherent pathways towards zero hunger. Different starting points will imply a unique trajectory for each community to attain food security. Modelling tools may better capture the complex interplay between social, ecological and economic factors that drive food security (Hammond and Dubé, 2012). Tools such as agent-based modelling could take into account the dynamic and adaptive nature of food security and provide a virtual laboratory to test ideas (Heckbert *et al*., 2010). However, the use of predictive models can be misleading in this context. According to Kwakkel and Pruyt (2015) complex problems are frequently characterised by conflicting information, multiple actors and an inherent lack of a well-defined problem formulation. As a result there may be more than one plausible approach to define a system boundary and decide which components and mechanisms are of importance to model (Kwakkel and Pruyt, 2015).

Exploratory modelling and analysis (EMA) offers a systematic approach to explore synergies and trade-offs between different strategies to eradicate food insecurity. Using computational models as scenario generators it is possible to analyse complex social-ecological systems taking into account uncertainties (Kwakkel and Pruyt, 2013). Unlike predictive modelling, the output of EMA does not provide a surrogate of the target system. Instead, it delivers a computational experiment inferring how the world would behave if the various estimates and assumptions were correct (Bankes, 1993). To date, EMA has been applied to the study of climate change, economic policy and transport (Kann and Weyant, 2000; Lempert and Schlesinger, 2000; Zhao and Kockelman, 2002). EMA has proven useful for the design of policies that are robust to multiple scenarios and for the exploration of trade-offs amongst policies.

Although policy is often considered a 'top-down' process, Ghorbani *et al*. (2014) suggest that the implementation and realisation of policy is determined by the combined effect of bottom-up processes that emerge from interactions between actors. Despite this, Johnson (2015) argues that policy research has continued to focus upon aggregates and averages with limited regard for complexity. This chapter will explore the potential of EMA to address complexity and better take into account factors affecting the realisation of food security policy.

In order to do this, we will use Malawi as a case study. Malawi is a small landlocked country, home to approximately 15 million people. Between 2014 and 2016, a total of 3.6 million people are likely to remain undernourished (FAO *et al*., 2015). Over 50% of the population live on less than one US dollar a day and the proportion of ultra-poor people (defined as the proportion of population below the minimum level of dietary energy requirement) is highest within Southern Malawi at approximately 34.2% (Gondwe, 2014). The realisation of food security is particularly problematic within rural areas (Verduzco-Gallo *et al*., 2014). Here, over 90% of the rural population are dependent upon agriculture (NSO, 2012a). Small plot sizes, widespread soil degradation and a continued dependence upon rain fed agriculture leave households vulnerable to food insecurity (Sahley *et al*., 2005).

In order to explore how interactions between households and their environment lead to the emergence of community food security, an ABM was constructed by Dobbie *et al*. (submitted and chapter 3). The model simulates the behaviour of households within rural villages in Southern Malawi. It is based on the Sustainable Livelihoods Framework (SLF) (Chambers and Conway, 1991; Scoones, 1998) and considers food security outcomes of different livelihood strategies. The simulation tool quantifies food availability, access, utilisation and stability at both the household and village level, thereby taking into account the multidimensional nature of food security (Dobbie *et al.*, submitted and chapter 3).

This chapter will document an approach to use this model to identify pathways towards zero hunger within rural Malawi. The potential of EMA to balance synergies and trade-offs between productivist, nutritionist and social protection strategies will be explored. Rather than focus upon silver bullet solutions, we draw attention to the complexity of rural livelihoods and consider desirable, yet diverse pathways towards food security in changing environments dominated by uncertainty. The chapter begins by outlining a conceptual framework that links the three strategies to food security and forms the basis of EMA. Section 4.3 provides the methodology, including an introduction to the model and subsequent EMA. Section 4.4 presents key results. A discussion in Section 4.5 is followed by concluding remarks in Section 4.6.

4.2 Conceptual Framework

In order to conduct EMA, it is important to have a clear conceptual model of the system at hand. Three key strategies have dominated the food security policy agenda over the past few decades (Fig. 4.1). Productivist strategies are based on the belief that increasing food production will solve food insecurity. They stem from the claim that in order to feed the world in 2050, global food production will need to increase by 50-70% (Godfray *et al.*, 2010; Pretty *et al.*, 2010). According to Denning *et al.* (2009) within rural Malawi, increased productivity may be realized by closing the yield gap through enhanced use of inputs. Greater market access and improved road infrastructure may also accelerate agricultural productivity (Diao *et al.*, 2008). In addition, the establishment of household enterprises and non-agricultural employment opportunities may promote growth (Fox and Sohnesen, 2016).

Nutritionist strategies pay attention to interventions that address hidden-hunger which arises from vitamin and mineral deficiencies. Within Malawi, over 50% of households were found to be at risk of calcium, selenium and zinc deficiencies due to inadequate dietary supplies (Joy *et al.*, 2015). Grass roots projects such as The Soils, Food and Healthy Communities project have used education and participatory approaches to heighten the nutritional quality of household diets within Northern Malawi (Patel *et al.*, 2014). Improved access to fuel and clean water may also help alleviate food insecurity (Sola *et al.*, 2016). A study of four villages within central Malawi found switches to lower grade fuels led to a reduction in diet diversity with foods that require a long cooking time, such as dry beans, removed from the diet (Brouwer *et al.*, 1997). Waterborne diseases and chronic intestinal infections were found by Humphrey (2009) to undermine the nutritional status of individuals without sufficient access to safe drinking water and sanitation facilities.

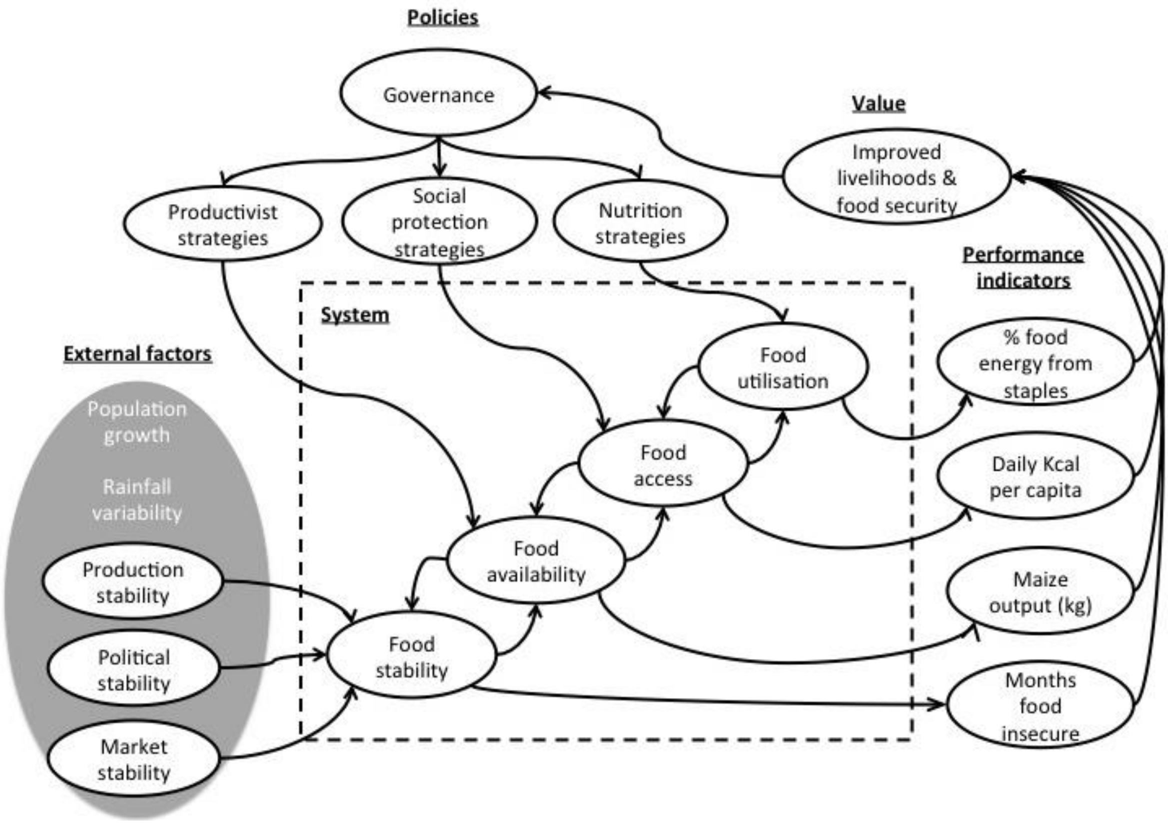

Figure 4.1: Conceptual model of food security.

Social Protection strategies advocate the introduction and maintenance of social safety nets such as payment for work and other cash transfer schemes (Barrientos and Hulme, 2009). Social protection can promote food security by stabilising and/ or raising incomes as well as enhancing social justice (Devereux, 2016). Within Malawi, public works programmes (PWPs) provide temporary employment. Individuals are paid in food or cash to carry out manual labour, such as constructing rural feeder roads or building schools (Devereux and White, 2010). In the short-term PWPs transfer food and/or cash to participants, whilst in the long-term they may improve rural infrastructure, promote agriculture and enhance livelihoods (Devereux, 2001; Devereux, 2016). A number of factors determine the ability of PWPs to address food security. These include the timing of the programmes, the salary, the social benefits of the projects and the costs associated with opportunities that households may have to forgo in order to accommodate temporary employment (Chirwa *et al.,* 2002).

In addition to PWPs, social cash transfer schemes have also been piloted within Malawi. Designed as a tool within the National Social Welfare Policy, The Malawi Social Cash Transfer Scheme (SCTS) was launched in 2006 (GoM, 2008). Under the scheme, elected Community Social Protection

Committees select the poorest 10% of households that have no assets, or consume only one meal a day and are labour constrained (Miller *et al*., 2010). By 2010 the SCTS operated within seven districts of Malawi encompassing over 83000 households. On average participating households received the equivalent of 14 USD per month (Miller *et al*., 2011). A study of 752 households by Miller *et al*. (2011) found that cash transfers led to significantly higher yields and improved dietary diversity.

The three strategies, productivist, nutritionist and social protection, act to address different elements of food security. Productivist strategies for example, are founded upon the availability of food, whilst social protection strategies tackle access and nutrition strategies focus upon food utilisation (Fig. 4.1). The ability of the four agendas to improve household livelihoods and food security status can be evaluated. In order to measure food security effectively, reviews by Jones *et al*. (2013) and Maxwell *et al*. (2014) suggest multiple indicators should be used with attention paid to the dimension of food security each measure represents. In this case, maize output in kg is used to monitor the availability of food. Daily food energy consumption per capita (kcal) evaluates food access. The proportion of dietary energy from staples is used as a proxy for food utilisation. Finally, the number of months a household is food insecure provides a measure of food stability.

The delivery mechanisms and outcomes of productivist, nutritionist and social protection strategies may overlap under certain circumstances. A number of recent studies for instance, suggest social protection strategies such as cash transfers may also enhance agricultural production (Todd *et al*., 2010; Boone *et al*., 2013). Despite a strong association with agriculture and increased production, input subsides can also represent social protection measures (Devereux and White, 2010). In a number of cases improved nutrition outcomes have also resulted from agricultural growth and access to cash transfers (Adato and Bassett, 2009). Benefits aside, there may also be instances where interactions between the strategies undermine efforts to alleviate food insecurity (Ellis and Maliro, 2013). However, relationships between productivist, nutritionist and/ or social protection measures have tended to be poorly conceptualised and are under-represented within coordinated policy agendas (Devereux, 2016). It is for this reason that the analysis described here focuses upon potential synergies between the three strategies and the identification of coherent pathways towards zero hunger.

Population growth and increased rainfall variability represent two external factors affecting the stability of markets, politics and agricultural productivity (Fig 4.1). In Malawi, the rural population is anticipated to grow from approximately 8.4 million in 1990 to almost 20 million by 2030 (UN, 2015c). It is likely that population growth will have wide ranging impacts upon land and labour availability as well as market prices and productivity (Headey and Jayne, 2014). A study of 1375 households within Malawi found areas of higher rural population density were associated with smaller farm sizes, lower agricultural wages and higher maize prices (Ricker-Gilbert *et al*., 2014).

Continued dependence upon rain-fed agriculture will leave households vulnerable to changes in rainfall frequency and intensity (Barrios *et al*., 2008). Rainfall is a key determinant of agricultural production and is connected to the economic and social wellbeing of rural communities (Haile, 2005). By 2050, maize production within Sub-Saharan Africa could decline by more than 20% (Wolfram and Lobell, 2010). Such reductions in the stability of crop productivity will act to undermine the realisation of community food security (Fig. 4.1)

4.3 Methods

4.3.1 Agent-based model

An ABM of rural food security in Southern Malawi was used for the analysis. The model was implemented using NetLogo (Wilensky, 1990). It explores how interactions between households and their environment lead to the emergence of food availability, access, utilisation and stability. Households are categorised into three different livelihood types, namely: farmers, agricultural labourers and non-agricultural workers. Household characteristics and behaviour correspond to the livelihood types, which were devised based upon an earlier cluster analysis of integrated household survey data (see Dobbie *et al*., in review and chapter 2).

During each monthly time step households go through a sequence of processes from resource allocation to harvesting crops and adopting coping strategies which combine to give outcomes in relation to land use, food production and food security status. This can be measured at both the household and village level. Food security is a function of food availability, access, utilisation and stability. A total of 12 time-steps constitute an agricultural season, running from June to May the following year. The livelihood strategy, or ‘type’ of a household may be adjusted at the end of an agricultural season. This is based upon the proportion of time allocated to farming, agricultural labour and non-agricultural work.

Throughout simulations described here, the model looped through 240 months, representing 20 years from 2010 to 2030. Three exogenous factors were simulated: population growth, rainfall and market variability. Population growth was based upon UN projections for Malawi (UN, 2015c). Annual rainfall was projected using MarkSim, a third-order Markov rainfall generator that can be employed as a Global Climate Model downscaler (Jones and Thornton, 2013). Market prices for crop and livestock products were modelled using two well established global models, AGLINK-

COSIMO (OECD and FAO, 2015) and GCAM4.0 (Kyle *et al*., 2011; Capellán-pérez *et al*., 2014). The simulation tool has been described in full by Dobbie *et al*. (submitted) and the model documentation and code is available online (https://www.openabm.org/model/5170/version/1/view).

In order to simulate cash transfers the model was extended to include an additional procedure. At the end of each year, households were ranked according to income. A proportion of the lowest income households were then selected to participate within a cash transfer scheme. For the following year, participating households received monthly cash payments. The proportion of households selected and the payment received was governed by two variables: *ct-value* and *ct-prop*, respectively. To take into account improvements in access to clean water and firewood, an additional variable, *pro-multi*, was used to enhance the processability of food. Values above 1 elevated the ability of a household to process and therefore utilise food.

4.3.2 Exploratory Modelling and Analysis

EMA comprised three stages (Fig. 4.2). Firstly, the model was used to generate outputs for multiple scenarios encompassing productivist, nutritionist and social protection strategies. In order to limit computational costs, results for just three variables concerning the proportion of food energy deficient farmers, agricultural labourers and non-agricultural workers were reported. Secondly, robust pathways towards zero hunger were identified using data mining techniques. Finally, food security outcomes of potential pathways were investigated further. Successful parameter sets were run again, this time reporting a wide range of indicators to take into account availability, access, utilisation and stability dimensions of food security. The three stages of EMA are described in greater detail throughout the remainder of this section.

In order to generate multiple scenarios for the first stage of the analysis, model parameters corresponding to each of the three strategies were first identified (see Table 4.1). Latin-hypercube (LHC) sampling was then used to create combinations of the different parameter values and provide simulation value sets. Parameter sampling was conducted using the R statistical package (https://www.r-project.org/) and the SPARTAN toolkit (Alden *et al*., 2013). LHC selects a value for each parameter from a specified range while ensuring efficient coverage of the parameter space and minimising correlations between chosen value sets (Helton and Davis, 2003). In line with Alden *et al*. (2013), a total of 500 simulation value sets were created. For each value set, the model was run using the R statistical package and the library RNetLogo (Thiele *et al*., 2012). A total of 50 replicate runs were made to minimise the effects of stochasticity upon model outcomes.

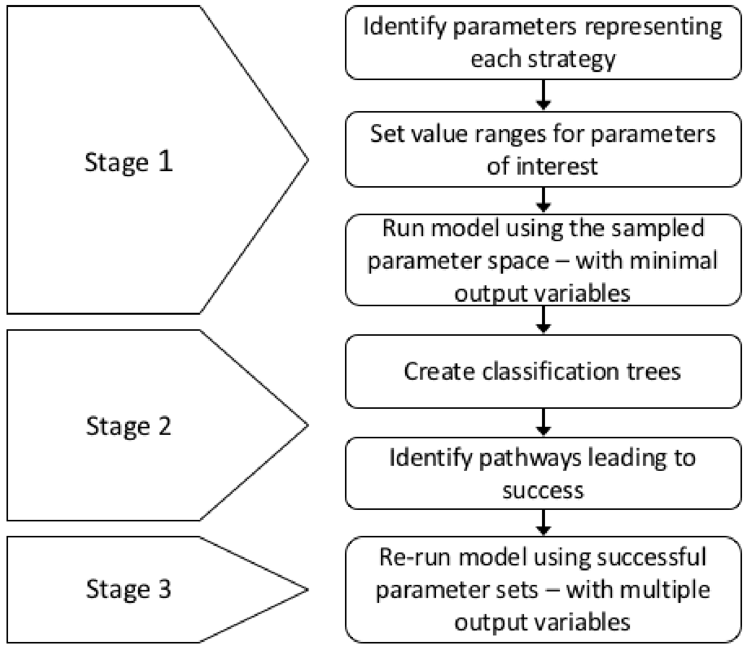

Figure 4.2: Overview of the three stages of the analysis.

At the end of each simulation run, the proportion of food energy deficient households was reported for each household type, namely farmers, agricultural labourers and non-agricultural workers. Model outputs corresponded to the end of the 2030-31 agricultural season running from June 2030 until May 2031. The mean value of 50 replicate runs for each of the simulation value sets was then calculated to provide a database of 500 simulation results to be used in the next phase of the analysis.

In order to identify scenarios leading to better food security outcomes, a binary variable was added to the database of results. Scenarios that led to less than 5% of the population being food energy deficient by the end of the agricultural year were given the value 'Success' and those, which did not, were given the value 'Fail'. The database was then used to grow a decision tree to identify different pathways towards successful outcomes.

Graphical 'trees' are generated by decision tree algorithms. Each branch of the tree relates to a decision (e.g. market efficiency > 0.8) and each leaf or node reports a classifier value (e.g. Success or Fail) (Witten and Edibe, 2005). Through iterative branching, the data is divided into smaller groupings until each group can be allocated a classifier with limited mis-classifications. The tree is pruned to prevent over-fitting (Witten and Edibe, 2005). A number of decision tree algorithms exist. The algorithm used in this paper is the C4.5 model (Quinlan, 1993).

Table 4.1: Parameter descriptions baseline values and sampling ranges in relation to the three food security strategies: productivist, social protection and nutritionist.

Strategy	Parameter	Description	Baseline value	Sampling range [low, high]
Productivist	*m-efficiency*	Market efficiency [proportion]	0.8	[0.8, 1]
	nag-avail	Availability of non-agricultural work [proportion]	0.8	[0.8, 1]
	p1-access *p2-access* *p3-access*	Probability of access to inputs (p1 = farmers, p2 = agricultural labourers, p3 = non-agricultural workers) [probability]	5.8 4.1 5.8	[5.8, 1] [4.1, 1] [5.8, 1]
Social Protection	*pw1-access* *pw2-access* *pw3-access*	Probability of access to food for work programmes (p1 = farmers, p2 = agricultural labourers, p3 = non-agricultural workers) [probability]	0.022 0.025 0.03	[0.022, 1] [0.025, 1] [0.03, 1]
	ct-value	Value of cash transfer [USD]	0	[0, 25]
	ct-prop	Proportion of low-income households with access to cash transfer [proportion]	0	[0, 1]
Nutritionist	*pro-multi*	Improvement to processability of food [multiplier]	1	[1, 1.99]

Using the RWeka library (Hornik *et al*., 2016), a tree was constructed incorporating the full database of 500 instances. In order to evaluate classification performance, 10-fold cross validation was then conducted. The RWeka library provides an estimate of errors by independently generating 10 separate decision trees each built from 90% of the data with 10% held back for validation. Mean results are then used to calculate a number of statistical measures including: Kappa statistic and Root mean squared error. A confusion matrix can also be generated to provide a breakdown of mis-classifications.

Once pathways towards zero hunger had been identified, the model was re run with successful parameter value sets. A single parameter set was selected at random for each pathway. A total of 200 replicate runs were conducted using each parameter set to reduce stochasticity. A number of indicators were used to capture the resulting availability, access, utilisation and stability dimensions of food security. These included: average monthly maize output (kg), mean daily food energy consumption per capita (kcal), proportion of food energy from staples (%) and the average number of months food insecure, respectively. This time, results were reported for each time step from 2010 to 2030. This allowed a more detailed evaluation of food security over time. To enable comparison, the model was also run using baseline values for parameters, representing a 'business as usual' scenario (see Table 4.1). One-way anova and Tukeys HSD were used to compare results across the different pathways and highlight significant differences with the 'business as usual' scenario.

4.4 Results

4.4.1 Decision tree analysis

A decision tree was grown from the outputs of 50 replicate simulation runs. The proportion of food energy deficient households defined whether pathways were successful or not. In this case, each of the household types, namely farmers, agricultural labourers and non-agricultural workers had to exhibit less than 5% food energy deficiency for a pathway to lead to success. The resulting tree takes into account the effect of climate, population and market projections by 2030. A total of six potential pathways were uncovered towards zero hunger by 2030 (Fig. 4.3)

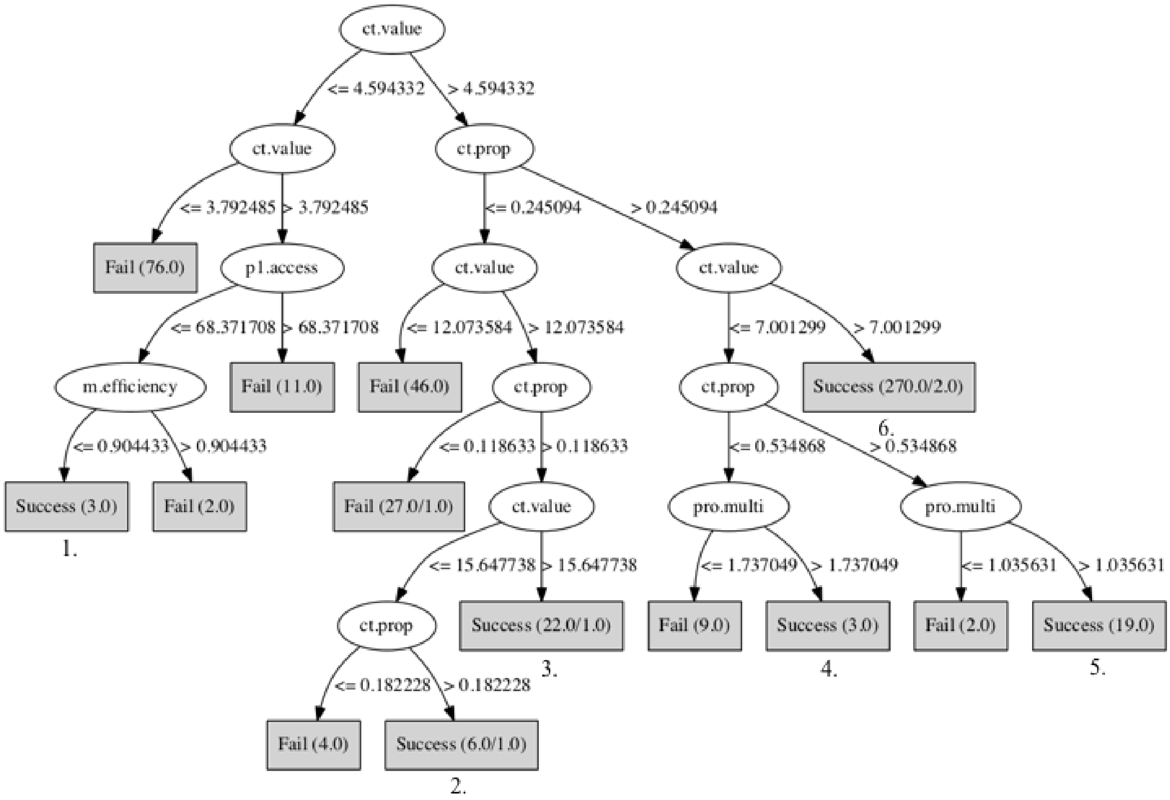

Figure 4.3: Decision tree of simulated food security outcomes by 2030. Success: less than 5% of farmers, agricultural labourers and non-agricultural workers are food energy deficient. Fail: more than 5% of households in any one category are food energy deficient.See Table 4.1 for variable descriptions.

A number of pathways related to social protection strategies, in particular social cash transfers. The value of the monthly cash transfer (in USD) forms the root of the tree. The first pathway balances social protection strategies with productivist strategies in the form of access to inputs and market efficiency. Cash transfers of between 3.8 USD and 4.6 USD help reduce the proportion of the population who are food energy deficient, in productivist contexts where access to inputs by famers is less than 70% and the efficiency of the market is less than 90%.

Pathways two and three are based upon the proportion of the population eligible for cash transfers and the value of the monthly payment. Higher cash transfer payments of greater than 15 USD mean low levels of household food energy deficiency (less than 5%) can still be achieved when a smaller proportion of the population are able to access payments. In pathway two, payments of up to 15.6 USD are sufficient, so long as more than 18% of the population has access to them. In pathway three, the proportion of households required to access cash transfers drops to less than 12% when payments are greater than 15.6 USD.

The fourth and fifth pathways combine social protection strategies with nutritionist strategies. When over half of the population has access to cash transfers of less than 7 USD, household food energy deficiency can be minimised if large improvements are made to the processability of food. Increasing the proportion of households with access to cash transfers further (in pathway 5) lessens the extent to which the processability of food needs to be improved.

Finally, pathway six favours inclusive cash transfer schemes with monthly payments greater than 7 USD. When almost a quarter of the population are eligible for cash transfers, the proportion of energy deficient households declines to less than 5%.

In order to explore the impact of different pathways upon the proportion of energy deficient households, outcomes of corresponding parameter sets are summarised (Fig. 4.4). The median value of food energy deficient households is less than 5% for all pathways. Interestingly, agricultural labourers have fewer energy deficient households when compared with non-agricultural workers and farmers. Pathways three and six perform best for all livelihood types in minimizing the number of food energy deficient households. However, pathway six has a number of outliers. This could be caused by mis-classifications, which occur when the decision tree incorrectly classifies parameter combinations as 'successful'. There may be some instances whereby parameter combinations adhere to the classification rules set by pathway 6, but result in greater than 5% of food energy deficient households, causing the parameter combinations to be incorrectly labelled as leading to 'success'.

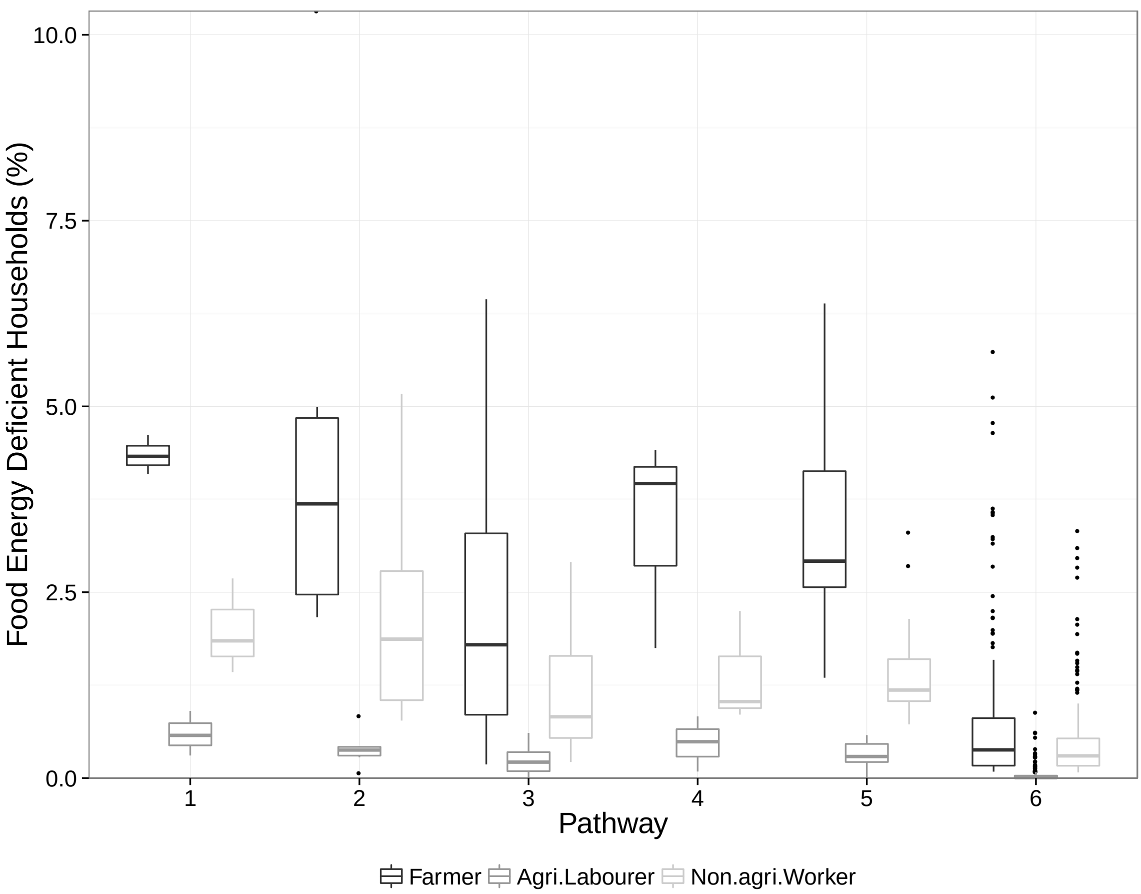

Figure 4.4: Comparison between the outcomes of pathways identified in Fig. 4.3.

Validation of the tree using 10-fold cross validation provided a number of error statistics. The Kappa statistic was used to quantify how similar the 10 independently generated decision trees were to one another. It provides a measure of the extent to which there is agreement other than that expected by chance (Cohen, 1960). In this case, a value of 83.6% implies almost perfect agreement (Landis & Koch 2008) and suggests that the resulting tree is highly stable. Root-mean-square error calculates the difference between classifications that are correctly and incorrectly predicted by the decision tree, respectively. A value of less than 0.3 instances suggests that predictions are highly accurate. This is reflected in the relative absolute error of 18.6%. Indeed, the proportion of correctly classified instances was high at 92.4% and the resulting confusion matrix reveals almost equal numbers of successes classified as fails (and vice versa) (Fig. 4.5).

$$\begin{pmatrix} S1 & S2 \\ F1 & F2 \end{pmatrix} = \begin{pmatrix} 162 & 18 \\ 20 & 300 \end{pmatrix}$$

Figure 4.5: Confusion matrix. Positions S1 and F2 are filled by the number of instances correctly assigned to classes 'success' and 'fail', respectively. Position S2 shows the number of instances of 'success' incorrectly assigned to 'fail' and similarly position F1 denotes the number of 'fail' instances wrongly assigned to class 'success'.

In order to gauge the effect of the outcome target upon the shape of the resulting tree, the process of constructing a tree was repeated three more times. The outcome target was varied to focus on less than or equal to 5% food energy deficiency within i) farmers only, ii) agricultural labourers only and iii) non-agricultural workers only, respectively. Interestingly, a focus on farmers led to the generation of the same tree (Fig. 4.3). However, differences could be found for agricultural labourers and non-agricultural workers (S1: Fig. 4.8). A total of four pathways to success were identified for agricultural labourers (S1: Fig. 4.8). Pathway one combines social protection and nutritionist strategies. The second pathway focuses upon social protection and productivist strategies. Finally, pathways three and four are based upon social protection strategies only. The tree for non-agricultural labourers was more complex. This is understandable as the households that make up this livelihood type are highly varied. Although the majority of a household's effort is spent upon non-agricultural activities, they do tend own livestock and may carry out some agricultural activities as well. As a result non-agricultural workers are likely to benefit from a broad range of policies. Almost half of the eighteen pathways led to success (S1: Fig. 4.8). Unlike the tree for agricultural labourers, in a number of cases combinations of all three strategies also lead to success. A total of four pathways combine social cash transfers with input subsidies and an enhanced ability to process food.

4.4.2 Food Security Outcomes

The model was re-run to explore food security outcomes of potential pathways identified within the decision tree in greater detail. Outcomes are summarised for each of the pathways and compared to baseline results (Table 4.2). Results refer to the average of 200 replicate runs and provide mean values and standard errors for the monthly food security status of households during the 2030-31 agricultural season.

One-way anova and Tukeys HSD were used to test for significant differences between outcome variables. No significant differences were found between each of the six pathways. Results for each of the outcome indicators were similar throughout. However, significant differences were uncovered between the outcomes of pathways when compared with baseline values. Daily food energy consumption per capita (kcal) for instance, was significantly higher for each of the pathways when compared with baseline results. This suggests that households had greater access to food under the 6 alternative pathways. The mean number of months for which households were food insecure was significantly lower. During the 2030-31 agricultural season, all paths except path 3 reported less than 1 month food insecure compared with more than 6 months for the baseline scenario. This implies greater food stability.

Table 4.2: Summary of food security outcomes at the household level for the different paths and baseline scenarios. Results are given for the average of 200 replicate runs, which correspond to the 2030-31 agricultural season.

	Average monthly maize output per household (kg)		Food energy consumption per capita (kcal)		Proportion of dietary energy from staples		Months food insecure	
	mean	SE	mean	SE	mean	SE	mean	SE
Baseline	14.9	1.2	1043.7*	19.1	82.3*	0.80	6.1*	0.03
Path 1	16.0	1.2	3127.2	29.0	99.0	0.03	0.1	0.03
Path 2	17.2	1.3	3138.9	27.1	99.0	0.03	0.1	0.01
Path 3	17.2	1.3	3139.9	27.1	99.0	0.03	0.6	0.53
Path 4	17.0	1.3	3152.9	27.3	99.0	0.03	0.1	0.02
Path 5	17.4	1.3	3133.6	28.0	99.0	0.03	0.1	0.02
Path 6	17.4	1.3	3168.1	27.0	99.0	0.03	0.0	0.01

* statistically significant pair-wise difference between the baseline scenario and each pathway at less than 5% level.

Interestingly, the proportion of dietary energy from staples was significantly higher for each of the six paths when compared with baseline values. Almost all calories were derived from staples such as maize, suggesting a trade-off between food access and utilisation. Improvements to food access and stability under the six pathways came at the expense of food utilisation. The only indicator not reporting a significant difference between baseline values and pathway outputs was average monthly maize output in kg. The mean output remained below 20 kg in all cases. This implies that the achievement of less than 5% of food energy deficient households occurred without significant increases in the production of their own food. Instead households were able to purchase food from local markets, or receive food from their social network.

In order to investigate the dynamic nature of food availability, access, utilisation and stability, the value of each of the corresponding indicators was plotted over time. Trends were similar across each of the six pathways. Attention is given here to path 6 as over half of the 500 sample parameter sets were grouped into this pathway (see Fig. 4.2). Results for the other pathways are provided as supplementary material accompanying this chapter (S2-S6: Fig. 4.9-Fig. 4.13).

A similar trajectory was found for maize output under both pathway 6 and the baseline scenario (Fig. 4.6A). The quantity of maize harvested peaked in February and again in April and May. The output of maize was highest for farmers, followed by non-agricultural workers and agricultural labourers. Differences could be seen between the daily food energy consumption per capita reported for path 6 and the baseline scenario. (Fig. 4.6B) Access to calories by all three household types remained stable at over 3000 kcal throughout the agricultural season. This was almost 3 times greater than the baseline scenario.

The stability of food access was also reflected in the number of months households were food insecure (Fig. 4.6C). Between 2010 and 2030, the baseline scenario showed an overall increase in the number of months households were food insecure. Perhaps surprisingly, under the baseline scenario, agricultural labourers experienced less food insecure months when compared with farmers and non-agricultural workers. However, this may be an artefact of small population sizes (See Fig. 4.7). Differences between the household types were minimized by path 6. The number of food insecure months was negligible for all household types.

Regarding utilisation, the proportion of food energy from staples was higher under path 6 throughout the entire agricultural season (Fig. 4.6D). There was little variation between household types. This contrasted strongly with the baseline scenario, here agricultural labourers tended to have a more diverse diet with a peak in the consumption of staples during February, April and May, corresponding to the maize harvest season.

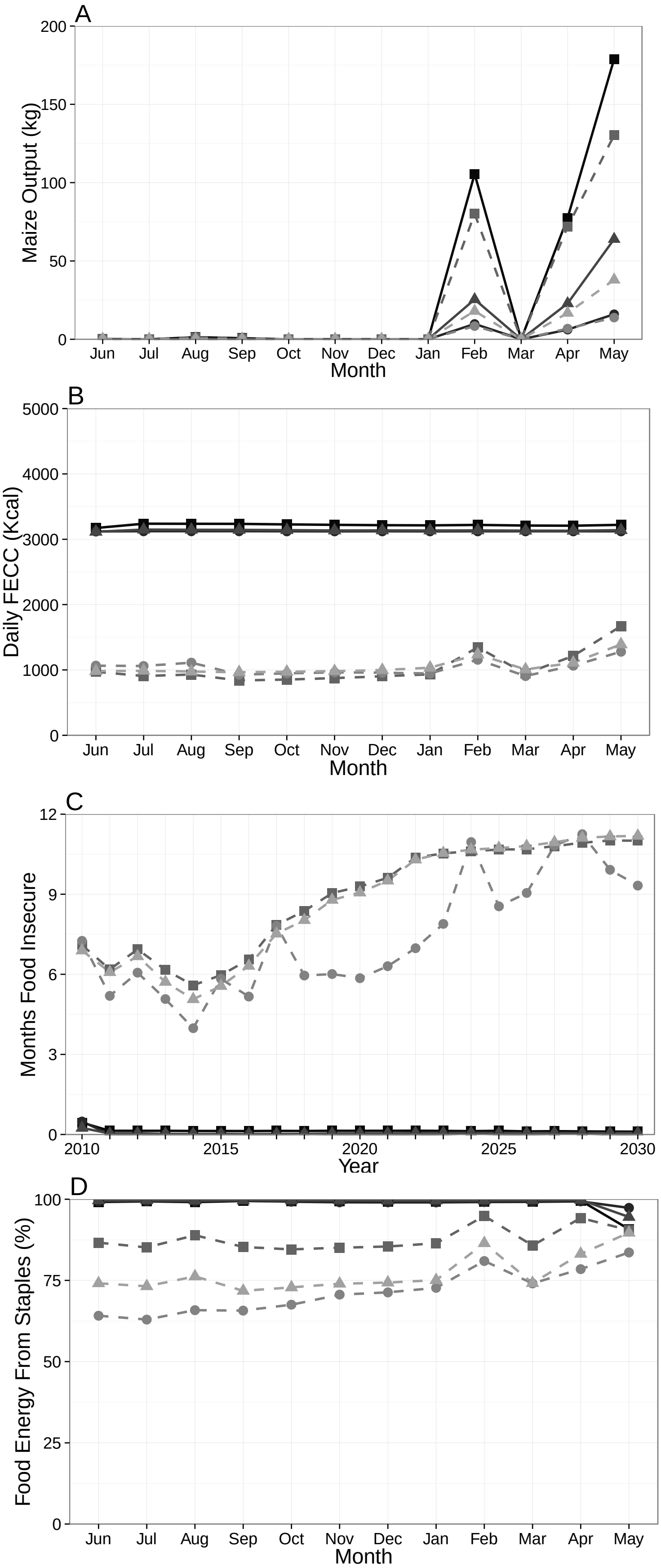
A
Maize Output (kg)
200
150
100
50
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May
Month
B
Daily FECC (Kcal)
5000
4000
3000
2000
1000
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May
Month
C
Months Food Insecure
12
9
6
3
0
2010 2015 2020 2025 2030
Year
D
Food Energy From Staples (%)
100
75
50
25
0
Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May
Month

Figure 4.6: Food security outcomes for path 6 (solid line) and baseline (dashed line) scenarios over time. Results are the average of 200 replicate runs. ☐Farmer; △ Agri. Labourer; ○ Non. Agri. Worker; A) average monthly maize output in kg; B) Daily food energy consumption per capita in kcal; C) Number of months food insecure; D) Proportion of food energy from staples (%).

At the end of each agricultural season, the livelihood strategy of households is updated based upon the amount of time spent upon farming, agricultural labour and non-agricultural work. Comparisons can be made between the proportions of different livelihood strategies over time (Fig 4.7). Under the baseline scenario, the proportion of agricultural labourers declines from 13% in 2010 to just 1% by 2030. Interestingly, under path 6, the proportion of agricultural labourers declines to a much lesser extent, comprising almost 10% of the population by 2030.

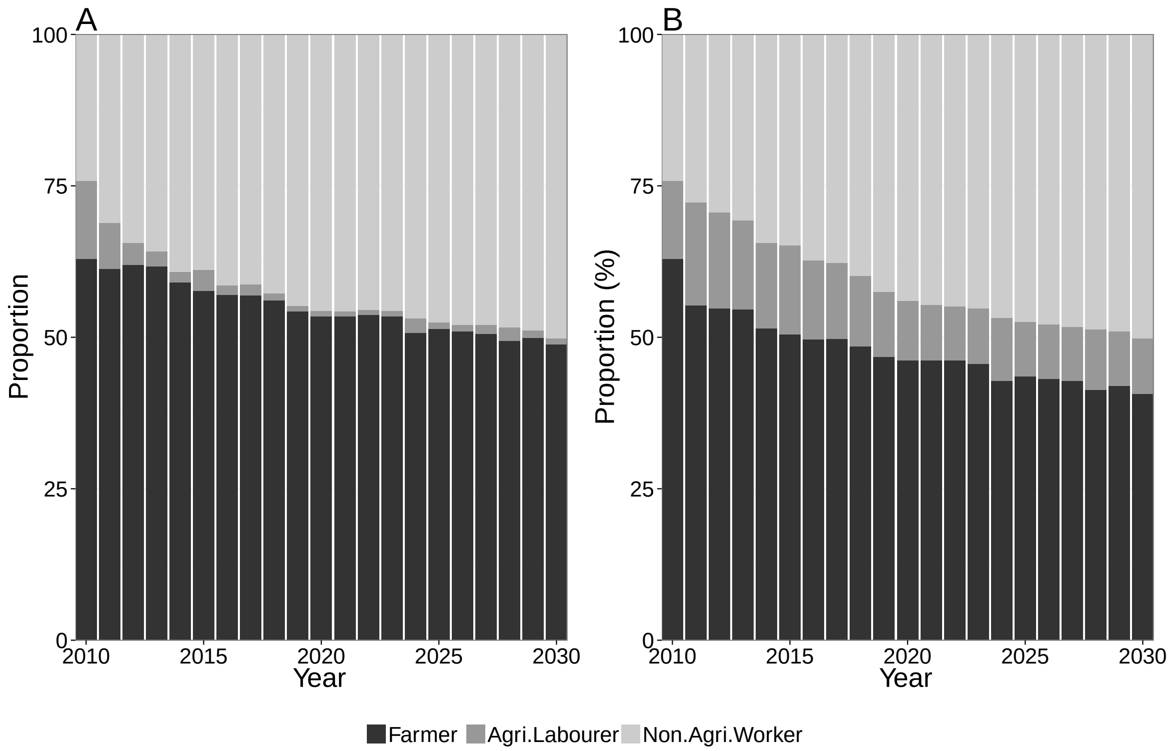

Figure 4.7: Proportion of different livelihood types over time. A) Baseline scenario; B) Path 6.

4.5 Discussion

Overall, the analysis conducted here demonstrates that it may be possible to navigate pathways towards zero hunger within rural villages of Malawi by 2030. Combinations of productivist, nutritionist and social protection strategies provided a number of coherent pathways towards zero hunger, defined by the attainment of less than 5% of food insecure households. Attention was given to the multidimensional nature of food security. Closer inspection of the pathways found a significant increase in both food access and stability when compared with 'business as usual'.

Interestingly however, improved food access and stability came at the expense of food utilisation. Behavioural rules represented within the model reflect an overwhelming food preference for maize amongst rural households within Malawi (Verduzco-Gallo *et al*., 2014). Diets high in staples however, are likely to lead to micronutrient deficiencies (Gibson *et al*., 2000). This can prove highly problematic with potentially irreversible implications regarding the physical ability and cognitive capacity of individuals (Gibson *et al*., 2000). Vitamin A deficiency is a leading cause of acquired blindness in children, for example (Kello and Gilbert, 2003).

Results from this study suggest that the selection of pathways towards zero hunger based upon achievement of household caloric requirements alone may overlook the micronutrient needs of households. To overcome this, favoured combinations of productivist, nutritionist and social protection strategies may be complemented with improved education and outreach surrounding good feeding practices. Nutrition education projects have already proven to be successful at enhancing the diversity of diets within Cambodia and Malawi (FAO, 2015a). Between 2008 and 2015 a total of 12000 farmers in Malawi were provided with nutrition education to improve infant and young child feeding (FAO, 2015a). An earlier pilot study found participatory nutrition led to the adoption of new feeding practices and significantly higher nutrient intakes (Hotz and Gibson, 2005). As part of the study, participatory techniques were used to engage community members (mothers and children aged 6 to 23 months) in an education intervention comprising four locally adapted lessons to promote complementary feeding practices (Hotz and Gibson, 2005).

It is important to acknowledge that the achievement of less than 5% of food insecure households came without any significant increase in maize output. Instead households increasingly accessed the market to meet their food needs through purchases of maize. Rethinking agricultural production initiatives to favour local production of vegetables might therefore promote more diverse diets and lead to improvements in food utilisation. Results from this study also provide further support for the role of social protection strategies in eradicating food insecurity. We have shown that increased emphasis placed upon social protection can lead to more stable access to food over time and a smaller disparity between the food security status of the three livelihood types.

Subtle differences in the success criteria were found to alter the shape of the resulting decision tree. By targeting either agricultural labourers or non-agricultural workers a different set of pathways towards zero hunger was generated. This highlights the important role of targeting in the alleviation of food insecurity (Berger *et al*., 2006; Miller *et al*., 2010; Houssou and Zeller, 2011). By paying attention to the circumstances under which farmers, agricultural labourers and non-agricultural workers achieved the same level of food energy consumption, the method adopted here provides a holistic approach that ensures each livelihood type can achieve food security. This echoes the prominence of more recent rights-based approaches to food security. Community food security for example, dictates that all residents of a community must obtain a safe, culturally acceptable and nutritional diet through sustainable means (Hamm and Bellows, 2003). This conceptualisation of food security emphasises the complex nature of food systems, which are embedded within dynamic social, ecological and economic processes (Thompson and Scoones, 2009; Kaiser, 2011).

4.5.1 Study Limitations

It is important to acknowledge the limitations of the approach. The need to be mindful of computational capacity led to a narrow view of each of the three strategies. Productivist, nutritionist and social protection strategies were represented by a small number of parameters. These were selected as they are well documented throughout the literature and represent some of the preferred mechanisms with which to deliver the three strategies. However, the simplification of productivist, nutritionist and social protection strategies into one or two delivery mechanisms may limit the scope of the analysis.

In addition to input subsidies and improved market access for instance, sustainable intensification has been put forward as a means to increase productivity (Pradhan *et al*., 2015). Here, attempts are made to produce more output from the same area of land while reducing the negative environmental impacts of intensification (Pretty, 2008). At the community level, this translates into activities such as agroforestry, conservation agriculture, integrated pest management and aquaculture (Pretty *et al*., 2011). These activities were not captured by the model. Nutritionist strategies described throughout the course of this study focused upon the ability to process food. This highlighted the impact of water and fuel access upon the food security status of households (Benson, 2015). The role of improved nutrition education however, could not be taken into account by the simulation. Other approaches to address nutrition, such as the fortification of foods (Darnton-Hill, 1998; Nilson and Piza, 1998) and improved sanitation (Ngure *et al*., 2014) were also neglected. For social protection, we focused attention on social transfers and employment creation. This overlooks other strategies such as school feeding programmes (Bundy *et al*., 2009) and weather indexed crop insurance (Barnett and Mahul, 2007).

The number of different scenarios that could be explored using EMA was also limited by computational power. We focused on identifying coherent combinations of the three strategies that were robust to population growth, projected market prices and climate change. Due to the relatively complex nature of the model, which takes into account the multidimensional nature of food security, we only considered a single scenario for each of the exogenous factors. Running multiple scenarios for climate change, population growth and projected market prices would enable a larger uncertainty space to be taken into account and more robust pathways to food security to be investigated.

The exploratory nature of this study offers an unbounded approach to the identification of pathways towards zero hunger. It is assumed that there are no constraints to the delivery of the various mechanisms associated with productivist, nutritionist and social protection strategies. This is a clear over-simplification that enables all possible outcomes to be explored. A number of factors will however limit the ability of identified pathways to be put into practice. For example, implementation capacities for managing social cash transfer schemes are weak in low income African countries (Schubert and Slater, 2006). Economists have argued that large scale agricultural input subsidies are expensive and can distort agricultural markets (World Bank, 1981). Within Malawi, Dorward and Chirwa (2009) found the 2008/9 farm input subsidy programme accounted for 16.2% of the national budget and 6.6% of GNP. Returns to investment in rural road infrastructure, which would improve market efficiency, are also met with long time-lags (Mwase, 2003).

Finally, there is evidence of conflicting results within the literature. A study of 752 households by Miller *et al*. (2011) found that cash transfers within Malawi led to significantly higher yields and improved diet diversity. In contrast, the results of EMA reported here uncovered no significant difference between the maize outputs of pathways dominated by social protection strategies when compared with the baseline scenario. Furthermore, the increase in social cash transfers and payment for work schemes was associated with reductions in dietary diversity over time. This is likely to be due to an increase in the amount of maize purchased from local markets.

Findings from this analysis do, however, corroborate relationships uncovered by Barrett and Bevis (2015). These authors found that indicators of micronutrient deficiency were much less responsive to growth in global national income (GNI) per capita than those associated with macronutrient intake. Comparison of national income and malnutrition measures for a number of counties found that the prevalence of wasting (caused primarily by insufficient macronutrient consumption) declined rapidly with growth in a country's GNI (Barrett and Bevis, 2015). This led Barrett and Bevis (2015) to conclude that individuals increase macronutrient intake fairly immediately with a rise in income, whilst improvements in micronutrient consumption tend to lag behind.

4.5.2 Future Work

An analysis of the benefits and challenges associated with each of the pathways should be undertaken to determine which strategies could feasibly be put into practice. Attempts should also be made to take into account additional climate change, population growth and market price scenarios. This will enable the identification of pathways that are robust against a wider range of uncertainty.

Attention should also be focused on the graduation from agricultural subsidies, nutrition interventions and social protection strategies. Graduation is important regarding the cost effectiveness of strategies to alleviate food insecurity. Providers are able to scale down operations and reduce costs over time (Sabates-Wheeler and Devereux, 2013). It is likely that governments will be more willing to support pathways to zero hunger if the delivery mechanisms are time-bound or target beneficiaries are likely to exit programmes over time (Sabates-Wheeler and Devereux, 2013). According to Devereux (2011), careful consideration of graduation can also avoid 'dependency syndrome' amongst the beneficiaries.

Graduation aside, the model could also be extended to broaden the scope of each of the productivist, nutritionist and social protection strategies. It would be interesting to explore whether improved education and altered food preferences could minimise the trade-off between the utilisation of food and increases in food access and stability over time.

4.6 Conclusions

Although the target to *"end hunger, achieve food security and adequate nutrition for all, and promote sustainable agriculture"* (UN 2015b, p.18), is ambitious, results here suggest there may be possible pathways with which to navigate towards zero hunger within rural Malawi by 2030. A data driven approach has enabled synergies between different productivist, nutritionist and social protection strategies to be uncovered. Shortcomings of the approach are associated with limits to computational power which reduce the number of delivery mechanisms and scenarios that can be explored. Future work will need to consider the feasibility of the different pathways in practice, as well as consider the governance dimensions, which remained out of the scope of this analysis. Once addressed however, it is hoped that the systematic approach detailed here can help overcome the silver bullet mentality in tackling food security and instead, provide coherent and robust pathways towards zero hunger by 2030.

4.7 Supplementary Information

Figure 4.8: Decision tree of simulated food security outcomes by 2030. Success: less than 5% of A) agricultural labourers; B) non-agricultural workers are food energy deficient. Fail: greater than 5% of households are food energy deficient.

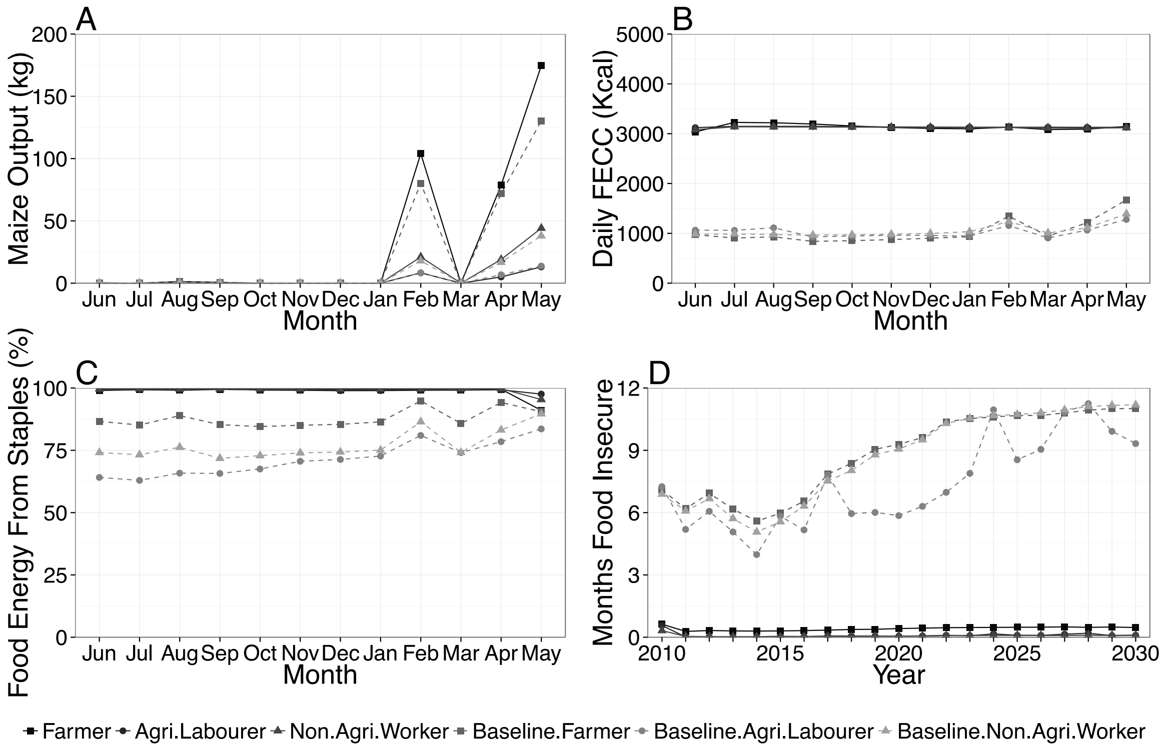

Figure 4.9: Path 1 food security outcomes A) monthly maize output; B) Daily food energy cons. per capita; C) Prop. of food energy from staples; D) No. of months food insecure.

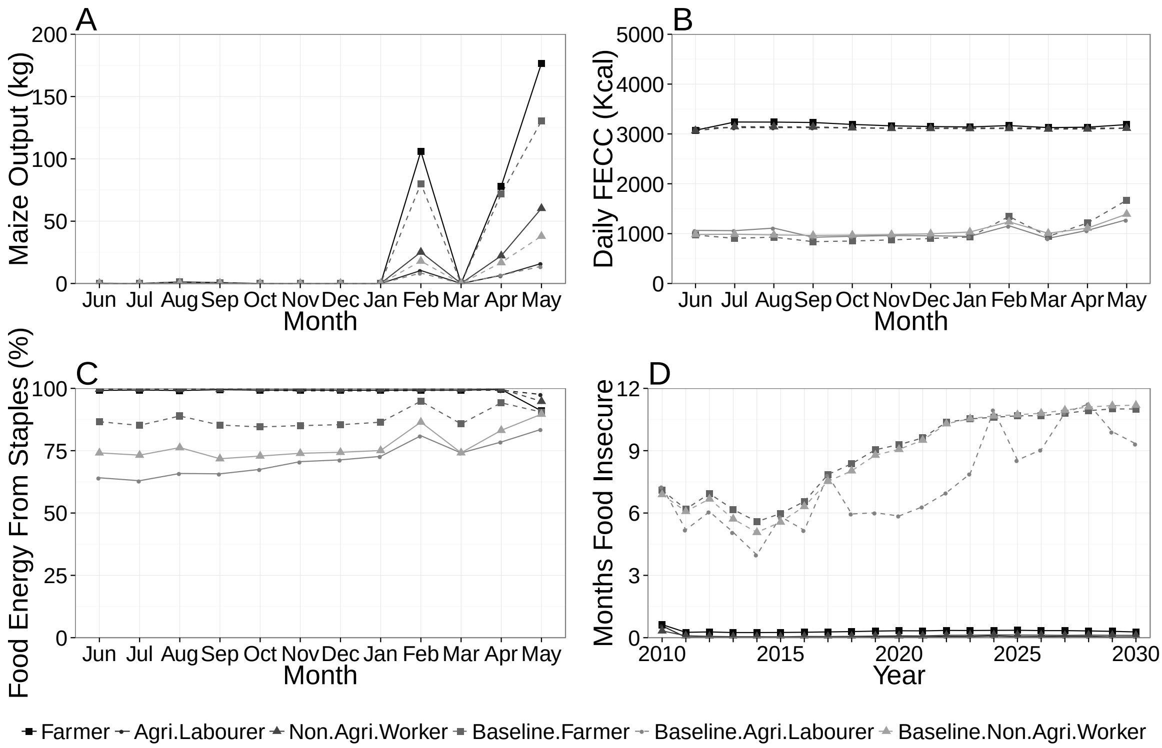

Figure 4.10: Path 2 food security outcomes A) monthly maize output; B) Daily food energy cons. per capita; C) Prop. of food energy from staples; D) No. of months food insecure.

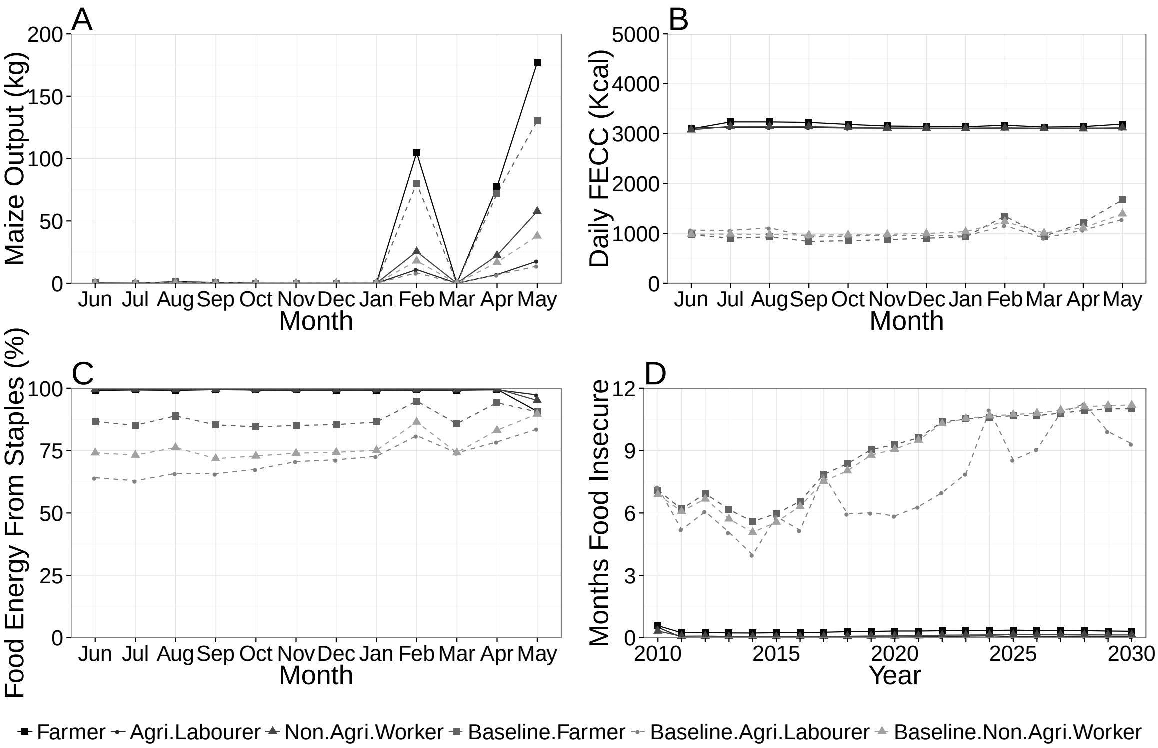

Figure 4.11: Path 3 food security outcomes A) monthly maize output; B) Daily food energy cons. per capita; C) Prop. of food energy from staples; D) No. of months food insecure.

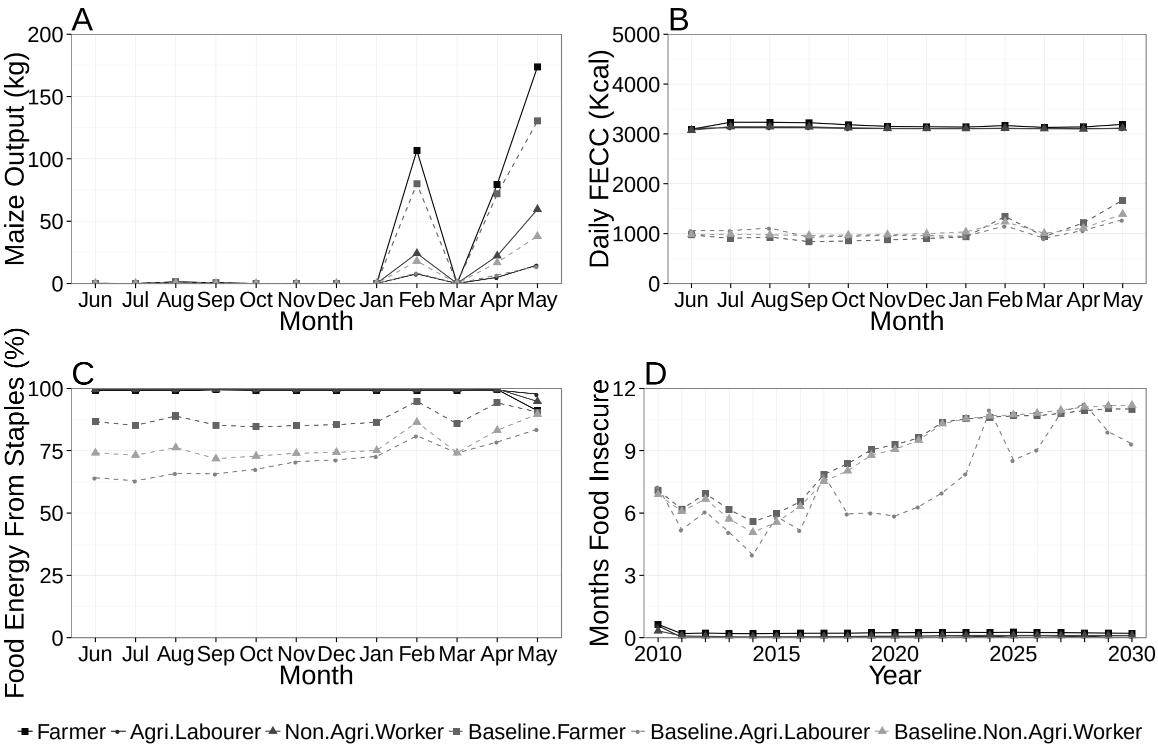

Figure 4.12: Path 4 food security outcomes A) monthly maize output; B) Daily food energy cons. per capita; C) Prop. of food energy from staples; D) No. of months food insecure.

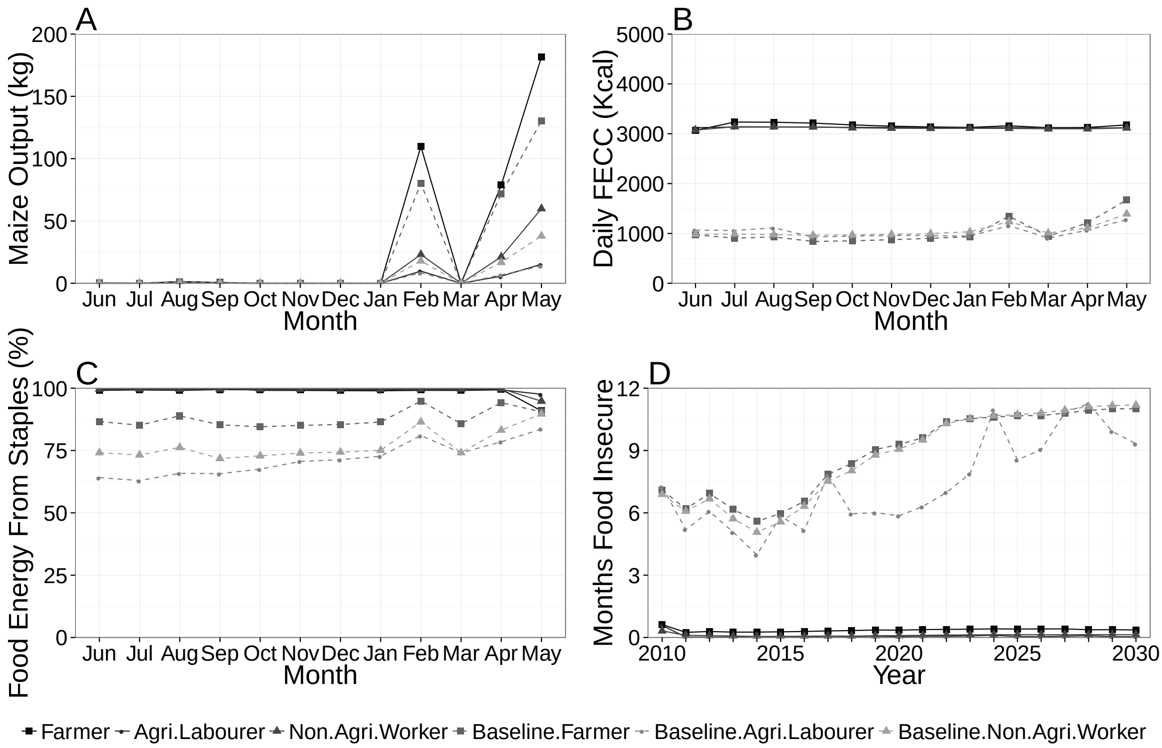

Figure 4.13: Path 5 food security outcomes A) monthly maize output; B) Daily food energy cons. per capita; C) Prop. of food energy from staples; D) No. of months food insecure.

Chapter 5: Discussion and Conclusions

5.1 Summary and Overview

This study documents the development of one of the first agent-based models to assess the availability, access, utilisation and stability dimensions of rural food security. During the course of the study, I have explored the ability of agent-based modelling to address the complexity of food security. Rural food systems are characterised by different forms of complexity including nonlinearity, uncertainty, emergence, scale and self-organization. This thesis drew upon the SLF to take into account the complex nature of livelihoods and investigate interactions between rural households, institutions and the environment.

In chapter two we described the use of cluster analysis to unpack the diversity of rural food systems and identify key livelihood strategies. The resulting household typology formed the basis of an ABM, which was documented within chapter three. We applied the model to explore the impact of population growth and increased rainfall variability upon the food security status of households. We paid particular attention to the multidimensional nature of the phenomenon, with an assessment of food availability, access, utilisation and stability.

In chapter four we drew attention to the uncertain nature of food security. Attempts were made to use the model in an exploratory manner to identify pathways towards zero hunger by 2030. Emphasis was placed upon identifying pathways that were coherent and robust. Such pathways balanced interactions between different policies in a coherent manner and were robust to population growth, changes in market prices and increased rainfall variability over time.

The aim of this final chapter is to draw together the main findings of the thesis, and to consider the future role of an agent-based modelling approach in addressing food insecurity within rural contexts. I will address the wider implications of this work and highlight limitations of the study. Areas where the research could be developed further are also documented. I begin with an overview of research findings taking into account the extent to which each of the six research questions identified within chapter one have been addressed throughout the course of this study. Attempts will be made to critically analyse what has been learned regarding the livelihood strategies of rural households, the development of empirical ABMs of food security and the identification of robust pathways towards zero hunger.

5.1.1 What are the key livelihood strategies of rural households within southern Malawi?

We used a quantitative, cluster-based analysis to identify three main livelihood types, namely farming households, agricultural labourers and non-agricultural workers. The livelihood types were found to be highly stable as further clustering attempts using different data sets uncovered the same household typology. The typology is formed based upon a small number of variables associated with household land, labour, livestock assets and gender. These variables are frequently collected using standard household survey instruments. As a result, the typology can be formed using a variety of different data sets and applied to different contexts. This is demonstrated in the third chapter of the thesis with the clustering of a village-level data set in Malawi.

In this case, identification of livelihood types rested upon an inductive approach. The degree to which typologies should be the result of deductive reasoning or inductive analysis, is the source of much debate (Emtage *et al*., 2007). For the former, the creation of individual or household typologies is based on theory or expert opinion, whilst the latter depends upon more quantitative techniques such as clustering (Rounsevell *et al*., 2012). Although statistical methods such as these offer a structured, repeatable and generalised approach to the construction of typologies, qualitative methods can provide greater depth of understanding. Jere (1997) used participatory diagnostic surveys to identify key variables to distinguish households. A mixed methods approach to typology formation therefore, could combine the benefits of both quantitative and qualitative methods (Emtage *et al*., 2007).

Application of the SLF provided us with greater understanding of the way in which households use their assets to form livelihood strategies. Comparisons could be made between the human, natural, financial, physical and social capitals of households. However, the selection of variables used to represent each of the five capitals proved difficult. There are no standard indicators to quantify the five capitals as the SLF has predominantly been used in development contexts, where indicators tend to be agreed at local level. In particular, attempts to quantify the social capital of households were met with misleading results. Variables isolated from the household survey data led to different conclusions regarding the social capital of farmers, agricultural labourers and non-agricultural workers. Alternative methods to assess social capital exist. Bodin and Crona (2008) demonstrate the use of social network analysis to assess social capital, for instance. Whereas, Van Rijn *et* al. (2012) describe a household survey instrument which distinguishes between structural and cognitive forms of social protection. Techniques such as these may benefit future attempts to quantify the social capital of households.

By operationalizing the sustainable livelihoods framework, we were able to investigate how the livelihood strategies of households might be shaped by the vulnerability context. Analysis of household survey data provided evidence of the frequency and severity of shocks experienced by households. Agricultural labourers were found to be more vulnerable to shocks, supporting a growing body of evidence regarding the link between 'ganyu' (casual) labour and vulnerable livelihoods (see Kerr, 2005; Bryceson, 2006; Sitienei *et al*., 2014).

Applications of the SLF are frequently criticised for overlooking the impact of transforming structures and processes (Carney, 2014). Using household survey data we were able to consider the effect of underlying policies, institutions and process upon the livelihoods of different household types. Both farmers and non-agricultural labourers for example, were more likely to have access to input subsidies than agricultural labourers. Interestingly, agricultural extension services also proved to be a vital source of advice for all households. A recent study by Chapota *et* al. (2014) explored the role of radio in strengthening the reach of agricultural extension services. This is part of a mounting body of evidence, which is beginning to explore the potential of communication for development (Agunga and Manda, 2014).

Perhaps surprisingly, the sustainability of livelihoods was difficult to assess using the SLF alone. Instead, we found the concept of household trajectories as framed by Dorward (2006) and Falconnier *et* al. (2015) useful. By exploring the ability of households to hang-in, step-up, step-out or fall-down, it was possible to make policy suggestions that were targeted to the specific needs of households.

5.1.2 How do the different livelihood strategies influence food availability, access, utilisation and stability?

Aggregate measures of household food security reported at the national or regional level have failed to capture variation between households. By operationalising the Sustainable Livelihoods Framework within chapter two, we have shown that it is possible to better understand how interactions between households within an environment lead to the emergence of food security outcomes

The three livelihood types identified in rural southern Malawi were found to differ in their food security outcomes, with almost 70% of agricultural labourers being food-energy deficient, compared with 65% of farmers and 60% of non-agricultural workers. Agricultural labourers were the most at risk of micronutrient deficiencies (Vitamin A, iron and zinc), followed by farmers and non-agricultural workers. When combined with knowledge of the vulnerability context and transforming structures and processes (outlined above), this provides a useful idea of how the different livelihood strategies translate into food security outcomes.

However, assumptions made when calculating food security outcomes using household consumption and expenditure surveys (HCES) may also have led to limitations. Intra-household food allocation patterns are not documented within food consumption data of the IHS3. As a result, food was assumed to be distributed in proportion to the energy and nutritional requirements of each individual household member. Studies by Katz (1995), Messer (1997) and Nanama and Frongillo (2012) have shown this is likely to be an oversimplification. Standard food security indicators, methodologies and cut-off points also need to be defined to allow comparisons between the results of different studies.

Despite this drawback, a livelihoods approach to the assessment of food security may still be of use, particularly when designing and targeting policies and development interventions. By unpacking the diversity of rural households into a small number of well-defined livelihood profiles, it is possible to tailor interventions more closely. This is an inclusive approach, which agrees with the underlying ethos of community food security, whereby all actors of a smallholder system attain sufficient quantities of culturally acceptable and nutritious food.

By restricting the analysis to household survey data, application of the SLF can only provide a snap shot in time. As the household survey data used to construct the typology covered only a single year, longer-term trends in population growth and land degradation could not be investigated. It was also not possible to explore the impact of potential policies or intervention strategies upon the food security status of different livelihood types. Such caveats could be overcome by the use of data from panel surveys.

5.1.3 Can agent-based modelling provide a useful tool to operationalise the sustainable livelihoods framework?

In order to address the dynamic, multi-scalar nature of food security, a review of the literature (in chapter one) uncovered the need to construct non-linear models. An investigation of potential simulation techniques concluded that agent-based modelling was the most suitable tool for unravelling the complexity of rural food security. Unlike mathematical modelling and systems dynamics, ABMs provide ideal tools for taking into account the heterogeneous nature of households and representing the emergence of macro-level behaviour from interactions at the local-level (Wijk *et al*., 2014).

The 'bottom-up' nature of agent-based modelling proved ideal for operationalising the SLF. It was possible to explore how local-level interactions between households and their environment might lead to the emergence of livelihood outcomes in the form of food security. Communicating the underlying model assumptions and mechanisms did prove difficult, however. A common criticism of ABMs is poor documentation and lack of transparency (Waldherr and Wijermans, 2013). Attempts to address this were made within chapter three with the use of the ODD+D protocol. This provides a clear explanation of the model aim, its entities and key procedures. Despite this, it is important to consider whether other techniques may be more appropriate for operationalising the SLF. A systems dynamics model for instance, may have been better at visualising feedback loops between the components of the SLF. The potential of an ABM to represent the SLF and unravel the complexity of household food security is discussed in greater detail within section 5.2.

5.1.4 How can an empirical ABM be constructed and validated in data scarce environments?

Heavier development and data costs associated with empirical ABMs, represent a downfall of the technique (Janssen and Ostrom, 2006). Within Malawi, collection of data at the community level has been uncoordinated and inconsistent. According to Jerven (2013) this is true throughout Sub-Saharan Africa. Chapter three provided a methodological approach to overcome challenges associated with the construction of ABMs within data scarce environments. Using a typology driven approach we demonstrated how an ABM can be formed from the integration of different data sources and the incorporation of both qualitative and quantitative knowledge.

We attempted to move away from agents exhibiting rational decision-making (Simon, 1955). Instead, we represented the behaviour of households using fast and frugal heuristics (Gigerenzer and Gaissmaier, 2011; Gigerenzer and Goldstein, 1996). This was implemented using decision trees, which were coded using simple 'IF ELSE' rules. We also used Fuzzy Logic to assess the availability, access, utilisation and stability of food at the household level (Zadeh, 1996). This provided a value between 0 and 100 from fuzzy linguistic rules, such as 'if processabilty is good then food utilisation is good'.

Application of the model allowed the effect of population growth, changing market prices and increased rainfall variability upon the food security status of households to be explored. Under the 'business as usual' scenario, significant declines in food utilisation and stability were uncovered by 2050. The model also enabled the trajectory of households to be traced over time. Livelihoods based upon either non-agricultural work or farming were found to be the most stable over time, but agricultural labourers, dependent upon the availability of casual work, demonstrated limited capacity to 'step-up' livelihood activities.

During the development of the empirical ABM, a number of additional limitations were uncovered. The aim of the model was to build upon the analysis of household survey data by taking into account the impact of long-term trends such as population growth and climate change. Although these exogenous processes were accounted for by the simulation tool, simplifications were required. Population growth, age structure, fertility, mortality and migration were not fully captured by the model. Furthermore, annual rainfall was used to characterise climate within the model. Yield was calculated using regression equations that take into account the accumulation of labour, fertiliser and rainfall. This overlooks temperature increases, along with more frequent shocks and stresses in the form of droughts and floods that are likely to result from climate change within Sub Saharan Africa (McSweeney *et al*., 2008). The link between shocks and stresses and food security is well documented throughout the literature (Baro and Deubal, 2006; Thornton *et al*., 2011; Tibesigwa *et al*., 2016). Chapter two of this thesis found households reported a decrease in income, food production and food stocks in response to shocks and stresses. It would be interesting for future work to explore the effect of such events on model outcomes.

In order to ensure credibility of results, we paid attention to model validation and the analysis of uncertainty. In chapter three we described the use of a role-playing game and comparisons with empirical data to validate the model. The role-playing game was used to validate the decision trees used to simulate the behaviour of households. Discussions with key stakeholders highlighted where model corrections were needed.

The output of model runs were also compared with a set of village data collected in 2014. Comparisons were made between observed and expected values for the number of months households were food insecure and the proportion of land households allocated to grain crops during the 2013-14 farming season. Results suggested that the model overestimates the number of months households are food insecure. However, this may be due to differences between validation data based upon perceived food security and model outputs, which measure the actual number of months households are food energy deficient. Experience based measures of food security, although easier and more cost efficient to collect, may result in a broad range of response bias (Jones *et al*., 2013).

In this case, a conscious decision was made not to fine-tune the model parameters based on existing empirical data. Epstein and Forber (2012) argue that tweaking mico-level parameters using macro-level data can undermine simulation tools, particular when they are based on 'bottom-up' approaches like agent-based modelling. Fine-tuning parameters comes with the risk of overfitting the simulation to the data (Epstein and Forber, 2012). Instead, efforts should be made to collect data with the sole aim of validating the ABM.

Analysis of model uncertainty can be used as a guide for future data collection. In this case, model uncertainty was investigated through consistency analysis and parameter robustness using SPARTAN, a statistical toolkit developed by Alden *et al*. (2013). This provided an indication of the number of simulation runs necessary to reduce technical uncertainty (in this case, 200 replicate runs were required) as well as determining the effect of parameter estimation on simulation results. Results of the uncertainty analysis suggest the ABM may be highly sensitive to parameters which are currently unknown. Data collection efforts should be directed towards those parameters which are highly sensitive.

Robinson *et al*. (2007) review a range of data collection methods which can be used to empirically ground ABMs. Sample surveys, participant observation, field and laboratory experiments and remotely sensed spatial data may be used to address prevailing research gaps, which have been identifed throughout the course of model development (Robinson *et al*., 2007).

Results from this study highlight the need for further research regarding the way in which households interact through their social networks. A study of 15 villages in Ethiopia by Hoddinot (2009) found households used their social networks as a means of obtaining credit for food or health expenses. Further studies have described risk sharing networks in Tanzania (De Weerdt and Dercon, 2006) and rural Philippines (Fafchamps and Lund, 2003). In addition to food sharing networks in Indonesia (Nolin, 2010). Despite this, we experienced difficulty in parameterising variables using existing data for rural Malawi. The number of times a household could call upon its social network for food in a given month for example, was hard to quantify.

5.1.5 Once built, can this simulation tool be used to identify robust pathways to zero hunger by 2030?

The final results chapter of the thesis applied the ABM to identify pathways towards zero hunger within rural Malawi. We outlined a conceptual framework which linked productivist, nutritionist and social protection strategies to food security. Although the framework was applied using Malawi as a case study, it may prove useful for a wide range of contexts. The framework could be adapted to explore factors affecting food security within a different case study country. Adjustments could also be made to investigate different performance indicators associated with food availability, access, utilisation and stability. In addition, the conceptual model could be used to take into account further policies, alongside those associated with productivist, social protection and nutritionist strategies. Finally, the framework could be altered to explore other external factors affecting the stability of markets and food production.

In this case the framework acted as a guide for subsequent EMA efforts using the ABM. A total of six pathways towards zero hunger were identified using techniques from data mining. These pathways ensured that less than 5% of households in each of the farmer, agricultural labourer and non-agricultural worker categories were food energy deficient by 2030.

Three limitations associated with the approach were identified. Firstly, due to model simplifications, only a small number of delivery mechanisms associated with productivist, nutritionist and social protection strategies could be explored. A number of additional delivery mechanisms are documented within the wider literature. For example, sustainable intensification (Pretty *et al*. 2011), fortification of foods (Nilson and Piza, 1998; Darnton-Hill 1998) and weather-based crop insurance (Barnett and Mahul, 2007).

Secondly, limits to computational power meant only a single scenario for each of the exogenous factors could be explored. Changes to population growth, rainfall variability and market prices were each based upon a single trajectory. This limited the uncertainty space that pathways towards zero hunger were robust to.

Finally, it was assumed that there were no constraints to the implementation of each of the productivist, nutritionist and social protection strategies. This is an oversimplification as a number of factors highlighted within chapter four (including implementation costs, timelags and market issues) are likely to limit the ability of pathways to be put into practice.

5.1.6 How can trade-offs and synergies between productivist, nutritionist and social protection strategies to zero hunger be harnessed?

Use of data mining techniques such as the creation of classification trees enabled synergies between productivist, nutritionist and social protection strategies to be uncovered. Classification trees provided a visual representation of pathways leading to less than 5% food energy deficiency by 2030. Interactions between variables associated with productivist, nutritionist and social protection strategies could be seen. For example, it was found that cash transfer payments of less than 4 USD could only alleviate food security in contexts characterised by high levels of market efficiency (up to 90%) and access to input subsidies by farmers (up to 70%). This represents a synergy between social protection strategies and productivist strategies, helping to overcome the silver bullet mentality, which has tended to dominate the food security discourse.

Closer inspection of the pathways uncovered the impact of the different strategies upon the availability, access, utilisation and stability of household food security over time. A trade-off was found between the utilisation of food and its increased access and stability. Interestingly, results suggested that the selection of pathways towards zero hunger based upon achievement of household caloric requirements alone may overlook the micronutrient needs of households. This highlights the need to pay attention to the food preferences of households when addressing food security. The ABM constructed throughout the course of this thesis, represents the overriding preference of Malawian households for diets rich in maize. Such dependence upon the staple crop is characteristic of countries throughout Sub-Saharan Africa (Shiferaw *et al*., 2011). Maize comprises more than 50% of total calories in Lesotho and Zambia and approximately 43% in Zimbabwe (Shiferaw *et al*., 2011). Although the crop provides vitamins A and E, it is deficient in lower B vitamins found within other grains such as sorghum and wheat (McCann, 2005). Furthermore, the staple food is low in protein and its leucine content inhibits absorption of niacin (McCann, 2005). Absence of this mineral has been found to lead to protein deficiency (McCann, 2005). As a consequence of this, there is growing recognition for the value of education programmes and interventions to increase the diversity of diets within Sub-Saharan Africa (Ruel *et al*., 2013).

5.2 Evaluating the Potential of Agent-based Modelling

The main aim of the thesis was to explore the potential of agent-based modelling to unravel the complexity of household food security. In this section I will address the potential of the ABM described throughout this thesis and move beyond the case study to consider the capacity of agent-based modelling more broadly. Attention will be given to the salience, credibility and legitimacy of the modelling approach.

5.2.1 Salience

In order to be salient, the model and its outputs must be suitable for the policy questions of interest and be readily accessible and comprehensible by decision makers (McNie, 2007). In this case, the model did provide a suitable environment to test the effect of long term trends such as population growth and climate change upon the food security status of households (see chapter 3). The ABM also provided a means to operationalise the conceptual model linking productivist, nutritionist and social protection strategies to the availability, access, utilisation and stability of food. Combined use of the ABM with EMA enabled pathways towards zero hunger by 2030 to be identified (see chapter 4). This directly addressed the Sustainable Development Goal to *"end* *hunger, achieve food security and adequate nutrition for all, and promote sustainable agriculture"* (UN 2015b, p.18).

Attempts were made to engage key stakeholders throughout the design, implementation and evaluation stages of the approach. A role-playing game for instance, was used to validate the behaviour of household agents and facilitate dialogue between experts from different scientific disciplines. However, a number of challenges were encountered. During the course of a modelling workshop, the simulation tool was met with several of the common criticisms outlined by Waldherr and Wijermans (2013). These included conflicting ideas such as 'your model is too complex', 'your model is too simple' and 'your model is not realistic'. Attempts were made to communicate the trade-off between reality, generality and precision often faced during model development (Levins, 1966). Despite this, stakeholders displayed unrealistic expectations, which could not be met by the simulation tool. This demonstrates the impact model construction has upon the salience of the resulting tool.

In this case, model development tended to be extractive, information was collated and synthesised by scientists and delivered to decision makers in a passive manner (i.e. through the development of journal articles and this thesis). Evidence of 'co-learning' (see Lynam *et al*., 2007) was limited to role-playing games and workshop discussions involving experts. In data scarce environments such as Malawi, the development of ABMs using secondary data may be cost effective and can provide a valuable method to integrate existing qualitative and quantitative data. However, this study has shown that minimising development costs can come at the expense of model utility. Smajgl (2010) emphasises the benefit of engaging stakeholders at each stage of the model development process using meetings and workshops. The participatory approach implemented by Smajgl (2010) was found to be very effective in creating research impact when considering sustainability issues in Indonesia.

Future studies developing models of food security within rural contexts may benefit from placing emphasis upon participatory approaches that elicit 'co-management' (Lynam *et al*., 2007). According to Hirsch *et al*. (2010) when selecting a particular participatory approach, attention should be given to the time required to prepare and apply the method, the context in which the method will applied and the need for careful training of local moderators. Techniques such as ethnographic decision tree modelling (Gladwin, 1989; Murray-Prior, 1998) and cognitive mapping provide participatory methods that could be used to complement existing household survey data and enhance the credibility of the simulation tool.

5.2.2 Credibility

To be credible, underlying model uncertainty and validity must be communicated effectively. In this case, the role-playing game did to a certain extent act to validate the ABM (see chapter 3). However, comparison of model outputs with a village data set proved problematic. The village data had not been collected with the aim of validating an ABM. As a result the types of questions asked and indicators provided were not ideal for making comparisons. Application of the SPARTAN toolkit however, did enable model uncertainty to be taken into account. The toolkit developed by Alden *et al*. (2013) provided a systematic approach to evaluate the number of model runs required to reduce the effect of stochasticity upon model outputs. It also provided a means to conduct local sensitivity analysis to test the impact of uncertain parameter values upon results (Alden *et al*., 2013).

According to Dearing *et al*. (2012), validating models of social-ecological systems against historical records may enable the credibility of the technique to be heightened. Complex social-ecological systems are path dependent and may operate upon multi-decadal time scales (Dearing *et al*., 2012). Knowledge of past processes, the existence of thresholds and the evolving nature of a system of interest may provide crucial insights regarding current and future behaviour *(Dearing et al.*, 2012).

Greater coordination of household surveys could therefore benefit food security analysis. Carletto *et al*. (2013) argue that the collection of a sufficient number of indicators, on a regular basis, by different stakeholders at the international level could be facilitated by repurposing existing survey instruments to better suit food security monitoring goals. A long-term, easily accessible, international dataset would aid the development and validation of ABM's using the generic methodology provided throughout the course of this thesis.

The 'black-box' nature of ABM's is a common criticism that results from poor documentation and acts to undermine model credibility (Grimm *et al*., 2006). Throughout this thesis we made a concerted effort to ensure the ABM was well documented. The code has been made available in full online, alongside a detailed ODD+D protocol. This is an extension of the more commonly used Overview, Design concepts and Details (ODD) protocol as it includes an explicit decision-making component (Müller *et al*., 2013). In addition to the ODD protocol and its revisions, a wide range of alternative documentation techniques also exist (Müller et al. 2014). For example, TRAnsperent and Comprehensive Ecological modelling (TRACE) provides a standard format for documenting the entire modelling cycle (Schmolke *et al*., 2010). Future applications of the methodology described within this thesis should consider whether (or not) such approaches could enhance the current documentation strategy.

5.2.3 Legitimacy

Finally, to be legitimate, realistic solutions must be provided that can be implemented in a timely manner (Bradshaw and Borchers, 2000). In chapter four of this thesis, the use of EMA to identify coherent and robust pathways to zero hunger was documented. However, the exploratory nature of this study offered an unbounded approach. Constraints to the delivery of the various mechanisms associated with productivist, nutritionist and social protection strategies were not taken into account (See chapter 4 for details).

There is a need to consider how ABMs developed using the methodology described in this thesis could be used as a boundary object between science and policy in practical terms. Within the context of ecosystem services, Willcock *et al*. (2016) provide one of the few studies investigating the implementation gap between ecosystem services research and its utilisation in practice. A survey of 60 technical experts within Sub-Saharan Africa found only 35% of respondents use information directly from models (Willcock *et al*., 2016). Reasons for the limited uptake of information from models included: lack of availability (54%) and/or the fact that technical experts do not feel capable of using this information (40%) (Willcock *et al*., 2016).

In order to bridge the implementation gap therefore, there is a need to prioritise capacity building efforts. Training centres and knowledge exchange partnerships should be instigated to enable models to be embedded within the decision making process. Adequate training coupled with an iterative science-policy process has been shown by Ruckelshaus *et al*. (2013) to be the most effective method to incorporate ecosystem services research into policy. Can an ABM alone set a country on the pathway to a more food secure future for all of its rural inhabitants? I would argue that the ABM described here provides one part of a suite of tools required to achieve this aim.

Indeed, a recent review by Orach and Schlüter (2016) highlights the fact that governance systems are themselves characterised by complexity. There is evidence to suggest that by failing to anticipate change or opting to ignore specific signals, governance may persist within undesirable states (Khan and Neis, 2010; Biesbroek *et al*., 2014; Candel, 2014). Although, models may play a number of useful roles throughout the policy process (Verburg *et al*., 2015), a wide range of tools may be required to promote the transition towards a food secure future. Selection of the toolset will depend upon which of a number of frameworks stakeholders use to understand the policy process of interest (Orach and Schlüter, 2016).

5.3 Future Work

Future work should address the limitations of this study and enhance the ability of agent-based modelling to address the complexity of rural food security. Regarding the ABM discussed throughout this thesis, enhanced credibility could be achieved by giving greater attention to empirical validation of the simulation tool. Attempts should also be made to advance the legitimacy of the ABM. Future work should investigate how to ensure the results of EMA are realistic and can be easily implemented.

Once these matters have been addressed, there is scope to apply the approach described in this thesis within a range of different contexts. This thesis provides a generic methodology for the use of household survey data in the development of an ABM to address rural household food security. There is potential to use the methodology to identify pathways to zero hunger within a number of countries reliant upon smallholder agriculture. In order to do this, household survey data would be required for the country in question. To ensure the resulting tool is salient, analysis of secondary data should be complemented with participatory fieldwork throughout the modelling process. The combined effort of multiple PhD students could greatly improve model building capacity and ensure the model outputs are highly credible and legitimate.

The true impact of this work may be realised by incorporating the model into an integrated modelling platform. ARtificial Intelligence for Ecosystem Services (ARIES) for example, represents a spatially explicit modelling framework for mapping and quantifying ecosystem services (Bagstad *et al*., 2014). Through semantic meta-modelling, the platform enables the integration of data and models from a wide range of sources (Bagstad *et al.*, 2014). The platform enables the user to assemble the appropriate models at the appropriate scales for the social-ecological context of interest. The use of a probabilistic approach based upon bayesian networks enables ARIES to address uncertainty explicitly (Bagstad *et al*., 2014). This allows decision makers to take into account the reliability of results when using the platform to inform policy.

Through collaboration with ASSETS and project partners, work is under way to use results from this thesis to inform a generic model of household behaviour. This will be incorporated into the ARIES modelling platform to create an integrated model of food security. Use of ARIES will enable additional scenarios corresponding to external drivers such as climate change and population growth to be taken into account. Application of the integrated model will also allow for greater understanding of how different strategies to achieve food security affect – and are affected by – ecosystem services.

5.4 Final Conclusions

This thesis has documented the development of one of the first ABMs to address the availability, access, utilisation and stability dimensions or rural food security. The nonlinear and multi-scalar nature of the phenomenon has been emphasised with attention given to uncertainty and the emergence of diverse livelihood strategies and food security outcomes. Agent-based modelling has proven to be a useful tool to operationalise the SLF and represent the multiplicity of interactions between households and the environment, which make up complex social-ecological systems.

The potential of agent-based modelling to unravel the complexity of rural household food security was evaluated with regards to the salience, credibility and legitimacy of the resulting simulation tool. The model was found to be highly salient. However, future work will need to enhance the credibility and legitimacy of the tool for it to be of use to decision makers. It is only then that the true potential of ABM in addressing the complexity of rural food security will be fulfilled.

References

Abdoulayi, U.S. et al., 2014. *Malawi Social Cash Transfer Program Baseline Evaluation Report*, North Carolina.

Adato, M. & Bassett, L., 2009. Social protection to support vulnerable children and families: the potential of cash transfers to protect education , health and nutrition. *Aids Care*, 21, pp.60–75.

Adriaenssens, V. et al., 2004. Fuzzy rule-based models for decision support in ecosystem management. *Science of the Total Environment*, 319(1-3), pp.1–12.

Agarwal, B., 1990. Social Security and the Family: Coping with Seasonality and Calamity in Rural India. *Journal of Peasant Studies*, 17(3), pp.341–412.

Agrawal, A. et al., 2013. Interactions between organizations and networks in common-pool resource governance. *Environmental Science and Policy*, 25, pp.138–146.

Agusdinata, B., 2008. *Exploratory modeling and analysis: A promising method to deal with deep uncertainty*. Delft University of Technology.

Ahmed, N. et al., 2010. Prawn postlarvae fishing in coastal Bangladesh: Challenges for sustainable livelihoods. *Marine Policy*, 34(2), pp.218–227.

Alden, K. et al., 2013. Spartan: a comprehensive tool for understanding uncertainty in simulations of biological systems. *PLoS computational biology*, 9(2), p.e1002916.

Allison, E.H. & Horemans, B., 2006. Putting the principles of the Sustainable Livelihoods Approach into fisheries development policy and practice. *Marine Policy*, 30(6), pp.757–766.

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling*, 229, pp.25–36.

Arhonditsis, G.B., 2009. Useless arithmetic? Lessons learnt from aquatic biogeochemical modeling. *Modelling of Pollutants in Complex Environmental Systems*, 1, p.1.

Ascher, W., 1978. *Forecasting: An Appraisal for Policy Makers and Planners*, Baltimore: Johns Hopkins University Press.

Agunga, R. and Manda, L.Z., 2014. Communication for strengthening agricultural extension and rural development in Malawi. *Journal of Development and Communication Studies*, *3*(1), pp.1-16.

ASSETS, 2011. *Project proposal: managing ecosystem services for food security and the nutritional health of the rural poor at the forest-agricultural interface. Internal Document.*

Babu, S.C., Thirumaran, S. & Mohanam, T.C., 1993. Agricultural productivity, seasonality and gender bias in rural nutrition: Empirical evidence from South India. *Social Science and Medicine*, 37(11), pp.1313–1319.

Bagstad, K.J., Voigt, B. & Johnson, G.W., A methodology for adaptable and robust ecosystem services assessment. *PloS one*, *9*(3), e91001

Balbi, S. & Giupponi, C., 2010. Agent-Based Modelling of Socio-Ecosystems: A Methodolgy for the Analysis of Adaption to Climate Change. *International Journal of Agent Technologies and Systems*, 2(4), pp.17–38.

Balbi, S. & Giupponi, C., 2010. Agent-based modelling of socio-ecosystems: a methodology for the analysis of adaptation to climate change. *International Journal of Agent Technologies and Systems*, 2(4), pp.17–38.

Bankes, S., 1993. Exploratory Modeling for Policy Analysis. *Operations Research*, 41(3), pp.435–449.

Bankes, S., 1993. Exploratory Modeling for Policy Analysis. *Operations Research*, 41(3), pp.435–449.

Baro, M. and Deubel, T.F., 2006. Persistent hunger: Perspectives on vulnerability, famine, and food security in sub-Saharan Africa. *Annu. Rev. Anthropol.*, *35*, pp.521-538.

Barlett, P., 1984. *Agricultural decision making: Anthropological contributions to rural development*, Academic Press.

Barnett, B.J. & Mahul, O., 2007. Weather index insurance for agriculture and rural areas in lower-income countries. *American Journal of Agricultural Economics*, 89(5), pp.1241–1247.

Barrett, C.B. & Bevis, L., 2015. The Micronutrient Deficiencies Challenge in African Food Systems. In D. E. Sahn, ed. *The Fight Against Hunger and Malnutrition: The Role of Food, Agriculture, and Targeted Policies*. Oxford: Oxford University Press, p. 384.

Barrientos, A. & Hulme, D., 2009. Social Protection for the Poor and Poorest in Developing

Countries: Reflections on a Quiet Revolution. *Oxford Development Studies*, 37(4), pp.439–456.

Barrios, S., Ouattara, B. & Strobl, E., 2008. The impact of climatic change on agricultural production: Is it different for Africa? *Food Policy*, 33(4), pp.287–298.

Becu, N. et al., 2008. Participatory computer simulation to support collective decision-making: Potential and limits of stakeholder involvement. *Land Use Policy*, 25(4), pp.498–509.

Beegle, K., Galasso, E. & Goldberg, J., 2014. *Direct and Indirect Effects of Malawi's Public Works Program on Food Security*, Washington, D.C.

Bengtsson, L. et al., 2015. Using mobile phone data to predict the spatial spread of cholera. *Scientific Reports*, 5, p.8923.

Benson, T., 2015. Association between irrigated farming and imporved nutrition in Malawian farm households. *Agrekon*, 54(3), pp.62–86.

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, 25(2-3), pp.245–260.

Berger, T., Schreinemachers, P. & Woelcke, J., 2006. Multi-agent simulation for the targeting of development policies in less-favored areas. *Agricultural Systems*, 88(1), pp.28–43.

Berkes, F., Colding, J. & Folke, C., 2008. *Navigating social-ecological systems: building resilience for complexity and change*, Cambridge University Press.

Bermudez, O.I. et al., 2012. Estimating micronutrient intakes from Household Consumption and Expenditures Surveys (HCES): an example from Bangladesh. *Food and Nutrition Bulletin*, 33(3), pp.208–213.

Berryman, A., 1991. Population theory: an essential ingredient in pest prediction, management, and policy-making. *American entomologist*, 37(3), pp.138–142.

Bert, F.E. et al., 2011. An agent based model to simulate structural and land use changes in agricultural systems of the argentine pampas. *Ecological Modelling*, 222(19), pp.3486–3499.

Bert, F.E. et al., 2014. Lessons from a comprehensive validation of an agent based-model: The experience of the Pampas Model of Argentinean agricultural systems. *Ecological Modelling*, 273, pp.284–298.

Biesbroek, G.R. et al., 2014. Analytical lenses on barriers in the governance of climate change adaptation. *Mitigation and Adaptation Strategies for Global Change*, 19(7), pp.1011–1032.

Binauli, L. et al., 2000. *Sustainable Livelihoods/ Poverty Reduction, Intra-household Distribution and Gender Aspects of Start Pack - Module 3*, Reading.

Bodin, Ö. and Crona, B.I., 2008. Management of natural resources at the community level: Exploring the role of social capital and leadership in a rural fishing community. *World development*, *36*(12), pp.2763-2779.

Bond, P., 2006. Global Governance Campaigning and MDGs: from Top-down to Bottom-up Anti-poverty Work. *Third World Quarterly*, 27, pp.339–354.

Boone, R. et al., 2013. Cash transfer programs and agricultural production: The case of Malawi. *Agricultural Economics*, 44(3), pp.365–378.

Boone, R.. & Galvin, K.., 2014. Simulation as an Approach to Social-Ecological Integration with an Emphasis on Agent-based Modeling. In J. Friedrichs, ed. *Understanding Society and Natural Resources: Forging New Strands of Integration Across the Social Sciences*. Springer Netherlands, pp. 67–92.

Bosma, R. et al., 2012. A generic methodology for developing fuzzy decision models. *Expert Systems with Applications*, 39(1), pp.1200–1210.

Bosma, R. et al., 2010. Using fuzzy logic modelling to simulate farmers' decision-making on diversification and integration in the Mekong Delta, Vietnam. *Soft Computing*, 15(2), pp.295–310.

Bousquet, F., Barreteau, O., d'Aquino, P., Etienne, M., Boissau, S., Aubert, S., Le Page, C., Babin, D. and Castella, J.C., 2002. Multi-agent systems and role games: collective learning processes for ecosystem management. *Complexity and ecosystem management: The theory and practice of multi-agent systems*, pp.248-285.

Box, G.E.P. & Draper, N.R., 1987. Empirical Model-Building and Response Surfaces. *Wiley Series in Probability and Mathematical Statistics*, p.669.

Bradshaw, G. & Borchers, J., 2000. Uncertainty as Information: Narrowing the science-policy gap. *Ecology and Society*, 4(1), pp.1–11.

Brady, M. et al., 2012. An agent-based approach to modeling impacts of agricultural policy on land use, biodiversity and ecosystem services. *Landscape Ecology*, 27(9), pp.1363–1381.

Brooks, J., 2014. Policy coherence and food security: The effects of OECD countries' agricultural policies. *Food Policy*, 44, pp.88–94.

Brouwer, I.D., Hoorweg, J.C. & van Liere, M.J., 1997. When households run out of fuel: Responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. *World Development*, 25(2), pp.255–266.

Brown, D.G. et al., 2013. Opportunities to improve impact, integration, and evaluation of land change models. *Current Opinion in Environmental Sustainability*, 5(5), pp.452–457.

Brown, K. et al., 2004. International Zinc Nutrition Consultative Group (IZiNCG) technical document# 1. Assessment of the risk of zinc deficiency in populations and options for its control. *Food and nutrition bulletin*, 25(1 Suppl 2), pp.S99–203.

Bryceson, D.F., 2006. Ganyu casual labour, famine and HIV/AIDS in rural Malawi: causality and casualty. *The Journal of Modern African Studies*, *44*(02), pp.173-202.

Bullock, S., 2014. Levins and the Lure of Artificial Worlds. *The Monist*, 97(3), pp.301–320.

Bundy, D. et al., 2009. *Rethinking school feeding: social safety nets, child development, and the education sector*, Washington, D.C.

Burchi, F. & Muro, P. De, 2016. From food availability to nutritional capabilities: Advancing food security analysis. *Food Policy*, 60, pp.10–19.

Cairns, J.E. et al., 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security*, 5(3), pp.345–360.

Candel, J.J.L., 2014. Food security governance: a systematic literature review. *Food Security*, *6*(4), 585-601.

Capellán-pérez, I. et al., 2014. *New climate scenario framework implementation in the GCAM integrated assessment model*, Bilbao.

CARE, 2002. *Household Livelihood Security Assessments A Toolkit for Practitioners*, Tucson, Arizona 2002.

Carletto, C., Zezza, A. & Banerjee, R., 2013. Towards better measurement of household food security: Harmonizing indicators and the role of household surveys. *Global Food Security*, 2(1), pp.30–40.

Cash, D.W. et al., 2003. Knowledge systems for sustainable development. *Proceedings of the*

National Academy of Sciences of the United States of America, 100(14), pp.8086–8091.

Castaing Gachassin, M., Najman, B. & Raballand, G., 2015. Roads and diversification of activities in rural areas: A cameroon case study. *Development Policy Review*, 33(3), pp.355–372.

Castella, J., Trung, T.N. & Boissau, S., 2005. Participatory Simulation of Land-Use Changes in the Northern Mountains of Vietnam: the Combined Use of an Agent-Based Model , a Role-Playing Game , and a Geographic Information System. *Ecology and Society*, *10*(1), 27.

Chamberlin, J. & Ricker-Gilbert, J., 2013. Participation in Rural Land Rental Markets in Sub-saharan Africa: Who Benefits and by How Much? Evidence from Malawi and Zambia. *American Journal of Agricultural Economics*, pp.1–33.

Chambers, R. & Conway, G., 1991. Sustainable rural livelihoods: practical concepts for the 21st century. *IDS Discussion Paper*, 296, p.29.

Chapota, R., Fatch, P. and Mthinda, C., 2014. The Role of Radio in Agricultural Extension and Advisory Services–Experiences and Lessons from Farm Radio Programming in Malawi–. *MEAS Case Study,(8)*.

Chaudhury, M. et al., 2013. Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Regional Environmental Change*, 13, pp.389–398.

Chibwana, C., Fisher, M. & Shively, G., 2012. Cropland Allocation Effects of Agricultural Input Subsidies in Malawi. *World Development*, 40(1), pp.124–133. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0305750X11000921 [Accessed June 7, 2013].

Chilongo, T., 2014. Livelihood strategies and forest reliance in Malawi. *Forests, Trees and Livelihoods*, 23(3), pp.188–210.

Chilowa, W., 1998. The impact of agricultural liberalisation on food security in Malawi. *Food Policy*, 23(6), pp.553–569.

Chirwa, E.W., Zgovu, E.K. & Mvula, P.M., 2002. Participation and Impact of Poverty-oriented Public Works Projects in Rural Malawi. *Development Policy Review*, 20(2), pp.159–176.

Christiaensen, L. & Todo, Y., 2014. Poverty reduction during the rural-urban transformation - The role of the missing middle. *World Development*, 63, pp.43–58.

Cohen, J., 1960. A Coefficient of Agreement for Nominal Scales. *Educational and Psychological Measurement*.

Conceição, P. et al., 2016. Toward a food secure future: Ensuring food security for sustainable human development in Sub-Saharan Africa. *Food Policy*, 60, pp.1–9.

Connolly-Boutin, L. & Smit, B., 2015. Climate change, food security, and livelihoods in sub-Saharan Africa. *Regional Environmental Change*, pp.385–399.

Coro, G. et al., 2015. Automatic classification of climate change effects on marine species distributions in 2050 using the AquaMaps model. *Environmental and Ecological Statistics*, 23(1), pp.1–26.

Coulibaly, J.Y., Gbetibouo, G.A., Kundhlande, G., Sileshi, G.W. and Beedy, T.L., 2015. Responding to crop failure: Understanding farmers' coping strategies in Southern Malawi. *Sustainability*, *7*(2), pp.1620-1636.

Cumming, G.S., Cumming, D.H.M. & Redman, C.L., 2006. Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. *Ecology and society*, *11*(1), 14.

Dantzig, G.B., 2002. Linear Programming. *Operations Research*, 50, pp.42–47.

Darnton-Hill, I., 1998. Overview: rationale and elements of a successful food-fortification programme. *Food and Nutrition Bulletin*, 19(2), pp.92–100.

Daskalopoulou, I. & Petrou, A., 2002. Utilising a farm typology to identify potential adopters of alternative farming activities in Greek agriculture. *Journal of Rural Studies*, 18(1), pp.95–103.

Deadman, P. et al., 2004. Colonist household decisionmaking and land-use change in the Amazon Rainforest: An agent-based simulation. *Environment and Planning B: Planning and Design*, 31(5), pp.693–709.

Dearing, J. a et al., 2012. Navigating the perfect storm: research strategies for socialecological systems in a rapidly evolving world. *Environmental management*, 49(4), pp.767–75.

Deaton, A., 1987. *The Allocation of Goods within the Household. Living Standards Measurement Study Working Paper*, Washington, D.C.

Denning, G. et al., 2009. Input subsidies to improve smallholder maize productivity in Malawi: Toward an African green revolution. *PLoS Biology*, 7(1).

Devereux, S., 2001. Livelihood insecurity and social protection: A re-emerging issue in rural development. *Development Policy Review*, 19(4), pp.507–19.

Devereux, S. et al., 2008. *Linking Social Protection and Support to Small Farmer Development*, *Malawi Case Study, FAO* Rome. Available at: http://eprints.soas.ac.uk/8893/.

Devereux, S., 2009. *Social protection for agricultural growth in Africa*, Brighton.

Devereux, S. & White, P., 2010. Social Protection in Africa: Evidence, Politics and Rights. *Poverty & Public Policy*, 2(3), pp.516–540.

Devereux, S., 2011. Social protection in South Africa: exceptional or exceptionalism? *Canadian Journal of Development Studies/Revue canadienne d'études du développement*, 32(4), pp.414–425.

Devereux, S., 2016. Social protection for enhanced food security in sub-Saharan Africa. *Food Policy*, 60, pp.52–62.

DFID, 1999. *Sustainable Livelihoods Guidance Sheets,* London. Available at: http://www.ennonline.net/dfidsustainableliving (Accessed January 20th 2016)

DFID, 2013. *New Alliance for Food Security & Nutrition in Malawi*, London.

Diao, X., Headey, D. & Johnson, M., 2008. Toward a green revolution in Africa: What would it achieve, and what would it require? *Agricultural Economics*, 39(SUPPL. 1), pp.539–550.

Dobbie, S., Dyke, J.G. & Schreckenberg, K., 2015. The use of participatory methods & simulation tools to understand the complexity of rural food security. In D. Bryde, Y. Mouzughi, & T. Al Rasheed, eds. *Sustainable Development Challenges in the Arab States of the Gulf*. Gerlach Press.

Dobbie, S. & Balbi, S., (2017). Design of an Empirical Agent-Based Model to Explore Rural Household Food Security Within a Developing Country Context. In *Advances in Social Simulation 2015* (pp. 81-94). Springer, Cham.

Dobbie, S., Dyke, J.G. & Schreckenberg, K., (in review) Unpacking Diversity: Typology Creation and Livelihoods Analysis to Support Food Security Policy in Rural Southern Malawi. *Food Security*.

Van Donge, J. K. (2002). Disordering the market: the liberalisation of burley tobacco in Malawi in the 1990s. *Journal of Southern African Studies*, *28*(1), 89-115.

Dorward, A., 1991. Integrated Decision Rules as Farm Management Tools In Smallholder Agriculture in Malawi. *Journal of Agricultural Economics*, pp.146–160.

Dorward, A., 1996. Modelling diversity, change and uncertainty in peasant agriculture in northern Malawi. *Agricultural Systems*, 51(4), pp.469–486.

Dorward, A., 2002. *A Typology of Malawian Rural Households*, Ashford, UK: Centre for Development and Poverty Reduction.

Dorward, A., 2003. *Modelling Poor Farm-household livelihoods in Malawi: Lessons for Pro-poor Policy*, London, UK.

Dorward, A., 2006. Markets and pro-poor agricultural growth: Insights from livelihood and informal rural economy models in Malawi. *Agricultural Economics*, 35(2), pp.157–169.

Dorward, A. et al., 2006. *Promoting agriculture for social protection or social protection for agriculture: Policy and research issues*, Available at: http://eprints.soas.ac.uk/5136/.

Dorward, A. et al., 2009. Hanging in, stepping up and stepping out: livelihood aspirations and strategies of the poor. *Development in Practice*, 19(2), pp.240–247.

Dostie, B., Haggblade, S. & Randriamamonjy, J., 2002. Seasonal poverty in Madagascar: Magnitude and solutions. *Food Policy*, 27(5-6), pp.493–518.

Dreze, J. & Sen, A., 1989. Hunger and Public Action. In Oxford University Press.

Dube, T. et al., 2016. The Impact of Climate Change on Agro-Ecological Based Livelihoods in Africa: A Review. *Journal of Sustainable Development*, 9(1), pp.256-267

Dury, J. et al., 2011. Models to support cropping plan and crop rotation decisions. A review. *Agronomy for Sustainable Development*, 32(2), pp.567–580.

Edmonds, B., 2004. *Against the inappropriate use of numerical representation in social simulation*, Manchester.

Edmonds, B., 2015. Using Qualitative Evidence to Inform the Specification of Agent-Based Models. *Journal of Artificial Societies and Social Simulation*, 18(1), p.18.

Ellis, F., 1998. Household strategies and rural livelihood diversification. *Journal of Development Studies*, 35(1), pp.1–38.

Ellis, F. & Bahiigwa, G., 2003. Livelihoods and rural poverty reduction in Uganda. *World Development*, 31(6), pp.997–1013.

Ellis, F. & Freeman, H.A., 2004. Rural Livelihoods and Poverty Reduction Strategies in Four African Countries. *Journal of Development Studies*, 40(4), pp.1–30.

Ellis, F., Kutengule, M. & Nyasulu, A., 2003. Livelihoods and rural poverty reduction in Malawi. *World Development*, 31(9), pp.1495–1510.

Ellis, F. & Maliro, D., 2013. Fertiliser Subsidies and Social Cash Transfers as Complementary or Competing Instruments for Reducing Vulnerability to Hunger: The Case of Malawi. *Development Policy Review*, 31(5), pp.575–596.

Ellis, F. & Manda, E., 2012. Seasonal Food Crises and Policy Responses: A Narrative Account of Three Food Security Crises in Malawi. *World Development*, 40(7), pp.1407–1417.

Ellis, F. & Mdoe, N., 2003. Livelihoods and rural poverty reduction in Tanzania. *World Development*, 31(8), pp.1367–1384.

Elsawah, S. et al., 2015. A methodology for eliciting, representing, and analysing stakeholder knowledge for decision making on complex socio-ecological systems: From cognitive maps to agent-based models. *Journal of environmental management*, 151C, pp.500–516.

Emtage, N., Herbohn, J. & Harrison, S., 2007. Landholder profiling and typologies for natural resource-management policy and program support: potential and constraints. *Environmental management*, 40(3), pp.481–92.

Emtage, N.F., 2004. Typologies of Landholders in Leyte , Philippines , and the Implications for Development of Policies for Small-Holder and Community Forestry. *Forestry*, (0), pp.81–88.

Englund, H., 2002. Ethnography after globalism : migration and emplacement in Malawi. *American Ethnologist*, 29(2), pp.261–286.

Epstein, J., 2008. Why model? *Journal of Artificial Societies and Social Simulation*, 11(4), p.6.

Epstein, J.M., 1999. Agent-Based Computational Models And Generative Social Science. *Complexity*, 4(5), pp.41–60.

Epstein, J.M. & Axtell, R., 1996. *Growing artificial societies: social science from the bottom up*, Brookings Institution Press.

Epstein, B. and Forber, P., 2013. The perils of tweaking: how to use macrodata to set parameters in complex simulation models. *Synthese*, pp.1-16.

Evenson, R.E. & Gollin, D., 2003. Assessing the impact of the green revolution, 1960 to 2000. *Science*, 300(5620), pp.758–62.

Fafchamps, M. and Lund, S., 2003. Risk-sharing networks in rural Philippines. *Journal of development Economics*, *71*(2), pp.261-287.

Falconnier, G.N. et al., 2015. Understanding farm trajectories and development pathways: Two decades of change in southern Mali. *Agricultural Systems*, 139, pp.210–222.

Fan, S., Gulati, A. & Dalafi, S., 2007. Overview of reforms and development in China and India. In A. Gulati & S. Fan, eds. *The Dragon & The Elephant: Agricultural and Rural Reforms in China and India*. Washington: IFPRI, pp. 10–44.

Fan, S., Olofinbiyi, T. & Gemessa, S., 2015. *Ending Hunger and Undernutrition by 2025: Accelerating the Pace* D. Sahn, ed., Oxford: Oxford University Press.

Fanzo, J.C. & Pronyk, P.M., 2011. A review of global progress toward the millennium development goal 1 hunger target. *Food and Nutrition Bulletin*, 32(2), pp.144–158.

FAO, 1983. *World food security: a reappraisal of the concepts and approaches. Director General's Report*, Rome.

FAO, 1996. *Rome declaration on world food security and World Food Summit Plan of Action. World Food Summit 13–17 November 1996*, Rome.

FAO, 2004. *Voluntary guidelines to support the progressive realization of the right to adequate food in the context of national food security*, Rome.

FAO, 2005. *Right to Food Guidelines*, Rome.

FAO, 2009. *Declaration of the World Summit on Food Security*, Rome.

FAO, 2015a. *Improving Complementary Feeding in Malawi: Lessons learned from a Process review of a food security and nutrition project*, Rome.

FAO, 2015b. *Review of food and agricultural policies in Malawi Country Report 2014*, Rome.

FAO, IFAD & WFP, 2015. *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress*, Rome.

Farmer, J.D. & Foley, D., 2009. The economy needs agent-based modelling. *Nature*, 460(7256), pp.685–686.

Ferrol-Schulte, D. et al., 2013. Sustainable Livelihoods Approach in tropical coastal and marine social-ecological systems: A review. *Marine Policy*, 42, pp.253–258.

Fiedler, J.L., Martin-Prevel, Y. & Moursi, M., 2013. Relative costs of 24-hour recall and household consumption and expenditures surveys for nutrition analysis. *Food and nutrition bulletin*, 34, pp.318–330.

Fine, D. et al., 2012. *Africa at work : Job creation and inclusive growth*, McKinsey Global Institute.

Folberth, C. et al., 2014. Effects of ecological and conventional agricultural intensification practices on maize yields in sub-Saharan Africa under potential climate change. *Environmental Research Letters*, 9(4), p.044004.

Fox, L. & Sohnesen, T.P., 2016. Household Enterprises and Poverty Reduction in Sub-Saharan Africa. *Development Policy Review*, 34(2), pp.197–221.

Fukuda-Parr, S., Yamin, A.E. & Greenstein, J., 2014. The power of numbers: A critical review of Millennium Development Goal targets for human development and human rights. *Journal of Human Development and Capabilities*, 15(2-3), pp.105–117.

Funtowicz, S. & Ravetz, J., 1990. *Uncertainty and quality in science for policy*, Springer Science & Business Media.

Galloway, R. et al., 2009. School feeding: outcomes and costs. *Food and Nutrition Bulletin*, 30(2)(2), pp.171–182.

Gebremedhin, L., Bezabih, M. & Gebreegziabher, Z., 2010. Local Social Networks, Shocks and Rainfall Patterns in the Highlands of Ethiopia. *EfD Ethiopia Working Paper*.

Gibson, R.S. et al., 2000. Dietary strategies to combat deficiencies of iron, zinc and vitamin A in developing countries: Development, implementation, monitoring, and evaluation. *Food and Nutrition Bulletin*, 21(2), pp.219–231.

Gigerenzer, G. & Gaissmaier, W., 2011. Heuristic decision making. *Annual Review of Psychology*, 62, pp.451–482.

Gigerenzer, G. & Goldstein, D.G., 1996. Reasoning the fast and frugal way: models of bounded rationality. *Psychological review*, 103(4), pp.650–69.

Gigerenzer, G. & Goldstein, D.G., 2011. The recognition heuristic : A decade of research. *Judgment and Decision Making*, 6(1), pp.100–121.

Gigerenzer, G. & Todd, P., 1999. Simple heuristics that make us smart. *Behavioral and Brain Sciences*, pp.97–118.

Giné, X. & Yang, D., 2009. Insurance, credit, and technology adoption: Field experimental evidence from Malawi. *Journal Of Development Economics*, 89(1), pp.1–11.

Gladwin, C.H., 1989. Indigenous knowledge systems, the cognitive revolution, and agricultural decision making. *Agriculture and Human Values*, 6(3), pp.32–41.

Godfray, H.C.J. et al., 2010. Food security: the challenge of feeding 9 billion people. *Science*, 327(5967), pp.812–8.

GoM, 2005. *Food and Nutrition Security Policy*, Lilongwe.

GoM, 2007. *Malawi Growth and Development Strategy: From Poverty to Prosperity 2006 - 2011*, Lilongwe. Available at: https://www.imf.org/external/pubs/ft/scr/2007/cr0755.pdf.

GoM, 2008. *Social Protection Policy. Social Protection: A Right for All. Fourth Draft.*, Lilongwe.

GoM, 2009a. *National Nutrition Policy and Strategic Plan*, Lilongwe.

GoM, 2009b. *The Malawi Growth and Development Strategy Annual Review 2009, an assessment of the annual achievements for the 2008/09 government financial year*, Lilongwe.

GoM, 2010. *National irrigation policy and development strategy*, Lilongwe.

GoM, 2011a. *Malawi Agricultural Sector Wide Approach*, Lilongwe.

GoM, 2011b. *Sun 1000 special days : 2011-2016 : national nutrition education and communication strategy for preventing child stunting in Malawi*, Lilongwe.

GoM, 2011c. *The National Agricultural Policy*, Lilongwe.

GoM, 2012. *Malawi National Export Strategy: 2013 - 2018*, Lilongwe.

GoM, 2013. *Situation of urbanisation in Malawi Report*, Mzuzu.

GoM, 2014. *G8 New Alliance for Food Security and Nutrition 2014 Annual Progress Report*, Lilongwe.

GoM, 2015a. *Malawi 2015 Floods Post Disaster Needs Assessment Report Malawi 2015 Floods*, Lilongwe

GoM, 2015b. *The cost of hunger in Malawi*, Lilongwe.

Gondwe, G., 2014. *2014 Millennium Development Goal Report for Malawi*, Lilongwe.

Greeven, S., 2015. *Society's response to climate change: A scenario discovery study using agent-based modelling*. Delft University of Technology.

Grimm, V. et al., 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling*, 198(1-2), pp.115–126.

Grimm, V. et al., 1999. Individual-based modelling and ecological theory: Synthesis of a workshop. *Ecological Modelling*, 115(2-3), pp.275–282.

Grimm, V. et al., 2010. The ODD protocol: A review and first update. *Ecological Modelling*, 221(23), pp.2760–2768.

Grosh, M.E. & Glewwe, P., 1998. Data Watch The World Bank's Living Standards Measurement Study Household Surveys. *The Journal of Economic Perspectives*, 12(1), pp.187–196.

Guyot, P. and Honiden, S., 2006. Agent-based participatory simulations: Merging multi-agent systems and role-playing games. *Journal of Artificial Societies and Social Simulation*, *9*(4).

Haile, M., 2005. Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1463), pp.2169–2182.

Haim, B., 2006. *Info-Gap Decision Theory: Decisions Under Severe Uncertainty, 2nd edition.*, London: Academic Press.

Hall, J.W. et al., 2012. Robust Climate Policies Under Uncertainty : A Comparison of Robust Decision Making and Info-Gap Methods. *Risk Analysis*, *32*(10), 1657-1672.

Hamarat, C. & Pruyt, E., 2011. Exploring the uncertainty of energy transitions: The case of world wind power. *2011 Proceedings of PICMET 11 Technology Management in the Energy Smart World PICMET*, (3), pp.1–10.

Hamm, M. & Bellows, A., 2003. Community Food Security and Nutrition Educators. *Journal of Nutrition Education and Behavior*, 35(1), pp.37–43.

Hammond, R. a & Dubé, L., 2012. A systems science perspective and transdisciplinary models for food and nutrition security. *Proceedings of the National Academy of Sciences of the United States of America*, 109(31), pp.12356–63.

Harrigan, J., 2008. Food insecurity, poverty and the Malawian Starter Pack: Fresh start or false start? *Food Policy*, 33(3), pp.237–249.

Harrigan, J., 1988. Malawi: The Impact of Pricing Policy on Smallholder Agriculture, *Development Policy Review*, *6*(4), 415-433.

Harrigan, J., 2003. U-Turns and Full Circles: Two Decades of Agricultural Reform in Malawi 1981–2000. *World Development*, 31(5), pp.847–863.

Hazell, P.B.R., 2009. The Asian Green Revolution. *Food Policy*, (November), pp.1–31.

Headey, D. & Ecker, O., 2013. Rethinking the measurement of food security: from first principles to best practice. *Food Security*, 5(3), pp.327–343.

Headey, D.D. & Jayne, T.S., 2014. Adaptation to land constraints: Is Africa different? *Food Policy*, 48, pp.18–33.

Heckbert, S., Baynes, T. & Reeson, A., 2010. Agent-based modeling in ecological economics. *Annals of the New York Academy of Sciences*, 1185, pp.39–53.

Hegre, H. et al., 2010. Predicting Armed Conflict, 2011 – 2050. *International Studies Quarterly*, *57*(2), 250-270.

Helton, J.C. & Davis, F.J., 2003. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. *Reliability Engineering and System Safety*, 81(1), pp.23–69.

Van Herzele, A. & Van Gossum, P., 2008. Typology building for owner-specific policies and communications to advance forest conversion in small pine plantations. *Landscape and Urban Planning*, 87(3), pp.201–209.

Hess, G., 1996. To analyse, or to simulate, is that the question? *American Entomologist*, 42, pp.14–16.

Hicks, N., 1979. Growth v. Basic Needs: Is There a Trade-Off? *World Development*, 7, pp.985–994.

Hillbruner, C. & Egan, R., 2008. Seasonality, household food security, and nutritional status in Dinajpur, Bangladesh. *Food and Nutrition Bulletin*, 29(3), pp.221–231.

Hirsch, D. et al., 2010. Participatory research for adaptive water management in a transition country - a case study from Uzbekistan. *Ecology and Society*, 15(3), pp.33.

Hirvonen, K., Taffesse, A.S. & Hassen, W.I., 2015. Seasonality and household diets in Ethiopia. *Public Health Nutrition*, *19*(10), 1723-1730.

Hoddinott, J., Dercon, S. and Krishnan, P., 2009. *Networks and informal mutual support in 15 Ethiopian villages*. International Food Policy Research Institute (IFPRI).

Holden, S.T. & Otsuka, K., 2014. The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. *Food Policy*, 48, pp.88–97.

Hornik, K. et al., 2016. *Package "RWeka,"* Available at: https://cran.r-project.org/web/packages/RWeka/index.html.

Hotz, C. & Gibson, R.S., 2005. Participatory nutrition education and adoption of new feeding practices are associated with improved adequacy of complementary diets among rural Malawian children: a pilot study. *European journal of clinical nutrition*, 59(2), pp.226–237.

Houssou, N. & Zeller, M., 2011. To target or not to target? The costs, benefits, and impacts of indicator-based targeting. *Food Policy*, 36(5), pp.626–636.

Howitt, R.E., 1995. Positive Mathematical Programming. *American Journal of Agricultural Economics*, 77(2), pp.329–342.

Humphrey, J.H., 2009. Child undernutrition, tropical enteropathy, toilets, and handwashing. *The Lancet*, 374(9694), pp.1032–1035.

Husson, F., Josse, J. & Pagès, J., 2010. Principal component methods - hierarchical clustering - partitional clustering: why would we need to choose for visualizing data? *Technical Report of the Applied Mathematics Department (Agrocampus)*, pp.1–17. Available at: http://factominer.free.fr/docs/HCPC_husson_josse.pdf.

IFAD, 2011. *Republic of malawi sustainable agriculture production programme*, Rome. Available at: http://www.ifad.org/operations/projects/design/104/malawi.pdf .

Imhoff-Kunsch, B. et al., 2012. Methods of using household consumption and expenditures survey (HCES) data to estimate the potential nutritional impact of fortified staple foods. *Food and nutrition bulletin*, 33(3), pp.185–189.

IOM, 2001. *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc*, National Academies Press.

Jakeman, A.J., Letcher, R.A. & Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. , 21, pp.602–614.

Jansen, H.G.P. et al., 2006. Policies for sustainable development in the hillside areas of Honduras: a quantitative livelihoods approach. *Agricultural Economics*, 34(2), pp.141–153.

Janssen, M. & Ostrom, E., 2006. Empirically Based , Agent-based models. *Ecology And Society*, 11(2), pp.37.

Janssen, S. & van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems*, 94(3), pp.622–636.

Jariseta, Z. et al., 2012. Comparison of estimates of the nutrient density of the diet of women and children in Uganda by Household Consumption and Expenditures Surveys (HCES) and 24-hour recall. *Food and nutrition bulletin*, 33, p.199s–207s.

Jarosz, L., 2014. Comparing food security and food sovereignty discourses. *Dialogues in Human Geography*, 4(2), pp.168–181.

Jayne, T.S., Chamberlin, J. & Headey, D.D., 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy*, 48, pp.1–17.

Jere, P., 1997. *Integrating farmer evaluations in integrated pest management research: concepts, experiences, and lessons.*, FSIPM Project.

Jerven, M., 2013. *Poor numbers: how we are misled by African development statistics and what to do about it*, Cornell University Press.

Joffre, O.M., Bosma, R.H., Ligtenberg, A., Ha, T.T.P. and Bregt, A.K., 2015. Combining participatory approaches and an agent-based model for better planning shrimp aquaculture. *Agricultural Systems*, *141*, pp.149-159.

Johnson, M.E., Masters, W.A. & Preckel, P. V., 2006. Diffusion and spillover of new technology: A heterogeneous-agent model for cassava in West Africa. *Agricultural Economics*, 35(2), pp.119–129.

Jones, A. et al., 2013. What are we assessing when we measure food security? A compendium and review of current metrics. *Advances in nutrition*, 4(5), pp.481–505.

Jones, P.G. & Thornton, P.K., 2013. Generating downscaled weather data from a suite of climate models for agricultural modelling applications. *Agricultural Systems*, 114, pp.1–5.

Joy, E.J.M. et al., 2015. Dietary mineral supplies in Malawi: spatial and socioeconomic assessment. *BMC Nutrition*, 1(1), p.42.

Kaiser, M.L., 2011. Food Security: An Ecological-Social Analysis to Promote Social Development. *Journal of Community Practice*, 19(1), pp.62–79.

Kalanda-Joshua, M. et al., 2011. Integrating indigenous knowledge with conventional science: Enhancing localised climate and weather forecasts in Nessa, Mulanje, Malawi. *Physics and Chemistry of the Earth, Parts A/B/C*, 36(14-15), pp.996–1003.

Kamanga, P., Vedeld, P. & Sjaastad, E., 2009. Forest incomes and rural livelihoods in Chiradzulu District, Malawi. *Ecological Economics*, 68(3), pp.613–624.

Kann, a & Weyant, J.P., 2000. Approaches for performing uncertainty analysis in large-scale energy/economic policy models. *Environmental Modeling & Assessment*, 5(1), pp.29–46.

Katz, E.G., 1995. Gender and trade within the household: Observations from rural guatemala. *World Development*, 23(2), pp.327–342.

Kerr, R.B., 2005. Informal labor and social relations in northern Malawi: The theoretical challenges and implications of ganyu labor for food security. *Rural sociology*, *70*(2), pp.167-187.

Kello, A.B. & Gilbert, C., 2003. Causes of severe visual impairment and blindness in children in schools for the blind in Ethiopia. *British Journal of Ophthalmology*, 87(5), pp.526–530.

Kelly, a, Becker, W. & Helsing, E., 1991. Food balance sheets. *WHO regional publications. European series*, 34, pp.39–48.

Khan, A.S. & Neis, B., 2010. The rebuilding imperative in fisheries: Clumsy solutions for a wicked problem? *Progress in Oceanography*, 87(1-4), pp.347–356.

Knox, J. et al., 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3), p.34032.

Korkalo, L., Hauta-alus, H. & Mutanen, M., 2011. *Food composition tables for Mozambique.*, Finland.

Kranton, R.E., 1996. Reciprocal exchange: A self-sustaining system. *The American Economic Review*, 86(4), pp.830–851.

Kwakkel, J., 2012. Exploratory system dynamics: a directed search for limits to global water use . *Proceedings of the 30th International Conference of the System Dynamics Society*, (2009), pp.1–14.

Kwakkel, J. & Pruyt, E., 2013. Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. *Technological Forecasting and Social Change*, 80(3), pp.419–431.

Kwakkel, J. & Pruyt, E., 2015. Using System Dynamics for Grand Challenges: The ESDMA Approach. *Systems Research and Behavioral Science*, 32(3), pp.358–375.

Kwakkel, J. & Slinger, J., 2012. A System Dynamics Model-Based Exploratory Analysis of Salt Water Intrusion in Coastal Aquifers . *Proceedings of the 30th International Conference of the System Dynamics Society*, (EEA 1999), pp.1–20.

Kwakkel, J.H., Walker, W.E. & Marchau, V.A.W.J., 2010. Classifying and communicating uncertainties in model-based policy analysis. *International Journal of Technology, Policy and Management*, 10(4), p.299.

Kydd, J., 1982. *Measuring peasant differentiation for policy purposes: A report on a cluster analysis classification of the population of the Lilongwe Land Development Programme, Malawi, for 1970 and 1979.*, Chancellor College: Department of Economics.

Kyle, P. et al., 2011. *GCAM 3.0 Agriculture and Land Use: Data Sources and Methods*, Richland, Washington.

Labadarios, D., 2005. Malnutrition in the developing world: The triple burden. *South African Journal of Clinical Nutrition*, 18(2), pp.119–121.

Landis, J.R. & Koch, G.G., 2008. The Measurement of Observer Agreement for Categorical Data Published by : International Biometric Society Stable URL : http://www.jstor.org/stable/2529310. *Society*, 33(1), pp.159–174.

Langyintuo, A. (2004). Malawi maize sector stakeholders workshop report. *Harare: CIMMYT-Zimbabwe*.

Lassi, Z.S. et al., 2013. Impact of education and provision of complementary feeding on growth and morbidity in children less than 2 years of age in developing countries: a systematic review. *BMC public health*, 13 Suppl 3(Suppl 3), p.S13.

Lê, S., Josse, J. & Husson, F., 2008. FactoMineR : An R package for multivariate analysis. *Journal of Statistical Software*, 25(1), pp.1–18.

Leffelaar, P.A., 1999. *On systems analysis and Simulation of ecological processes; with examples in CSMP, FST and FORTRAN*, Kluwer academic publishers.

Lele, U., 1990. Structural adjustment, agricultural development and the poor: Some lessons from the Malawian experience. *World Development*, 18(9), pp.1207–1219.

Lempert, R.J., Popper, S.W. & Bankes, S.C., 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*, Rand Corporation.

Lempert, R.J. & Schlesinger, M., 2000. Robust strategies for abating climate change. *Climatic Change*, 45(3), pp.387–401.

Leonard, W.R., 1991. Household-level strategies for protecting children from seasonal food scarcity. *Social Science and Medicine*, 33(10), pp.1127–1133.

Levins, R., 1966. The strategy of model building in population biology. *American Naturalist*, 54(4), pp.421–431.

Ligon, E. & Schechter, L., 2012. Motives for sharing in social networks. *Journal of Development Economics*, 99(1), pp.13–26.

Ligtenberg, A. et al., 2010. Computers , Environment and Urban Systems Validation of an agent-based model for spatial planning : A role-playing approach. *Computers, Environment and Urban Systems*, 34(5), pp.424–434.

Lintelo, D. & Lakshman, W.D., 2015. *The Hunger and Nutrition Commitment Index (HANCI 2014)*, Brighton.

Liu, J. et al., 2007. Complexity of Coupled Human and Natural Systems. *Science*, 317(5844), pp.1513–1516.

Loftsgard, L.D. & Heady, E., 1959. Agricultural & Applied Economics Association Application of Dynamic Programming Models for Optimum Farm and Home Plans. *Journal of Farm Economics*, 41(1), pp.51–62.

Low, A., 1974. Decision taking under uncertainty: a linear programming model of peasant farmer behaviour. *Journal of Agricultural Economics*, 25(3), pp.311–321.

Lynam, T. et al., 2007. A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society*, 12(1).

Macal, C.M. & North, M.J., 2010. Tutorial on agent-based modelling and simulation. *Journal of Simulation*, 4(3), pp.151–162.

Machálek, T. et al., 2013. Fuzzy Methods in Land Use Modeling for Archaeology. *Proc. of 31st International Conference on Mathematical Methods in Economics 2013, Jihlava, part II*, pp.552–557.

Mackinson, S., 2001. Integrating Local and Scientific Knowledge: An Example in Fisheries Science. *Environmental Management*, 27(4), pp.533–545.

Maes, K.C. et al., 2009. Food insecurity among volunteer AIDS caregivers in Addis Ababa, Ethiopia was highly prevalent but buffered from the 2008 food crisis. *The Journal of nutrition*, 139(9), pp.1758–64.

Maleta, K. et al., 2003. Seasonality of growth and the relationship between weight and height gain in children under three years of age in rural Malawi. *Acta paediatrica (Oslo, Norway : 1992)*, 92(4), pp.491–7.

Masanjala, W. H. (2006). Cash crop liberalization and poverty alleviation in Africa: evidence from Malawi. *Agricultural Economics*, *35*(2), 231-240.

Masters, W. et al., 2000. Evaluating Recent Strategies to Improve Food Security Among Smallholder Households in Malawi. USAID–IFPRI.

Matthews, R.B. et al., 2007. Agent-based land-use models: a review of applications. *Landscape Ecology*, 22(10), pp.1447–1459.

Maxwell, D., Vaitla, B. & Coates, J., 2014. How do indicators of household food insecurity measure up? An empirical comparison from Ethiopia. *Food Policy*, 47, pp.107–116.

May, R.M. & Oster, G.F., 2011. Bifurcations and Dynamic Complexity in Simple Ecological Models. The University of Chicago Press for The American Society of Naturalists.

Mazzocchi, F., 2008. Complexity in biology. Exceeding the limits of reductionism and determinism using complexity theory. *EMBO reports*, 9(1), pp.10–14.

McCann, J., 2005. *Maize and grace*. Harvard University Press.

McCullum, C. et al., 2005. Evidence-Based Strategies to Build Community Food Security. *Journal of the American Dietetic Association*, 105(2), pp.278–283.

McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental science & policy*, 10(1), pp.17–38.

McSweeney, C., New, M. & Lizcano, G., 2008. *UNDP climate change country profiles Malawi*, Available at: http://ncsp.undp.org/sites/default/files/Malawi.oxford.report.pdf.

Meadows, D.H., 2008. *Thinking in systems: a primer* D. Wright, ed., London: Earthscan.

Mena, C. et al., 2014. Land Use Change on Household Farms in the Ecuadorian Amazon: Design and Implementation of an Agent-Based Model. *Applied Geography*, 31(1), pp.210–222.

Merrien, F.X., 2013. Social Protection as Development Policy: A New International Agenda for Action. *International Development Policy*, 4(2), pp.89–106.

Messer, E., 1997. Intra-household allocation of food and health care: Current findings and understandings - Introduction. *Social Science and Medicine*, 44(11), pp.1675–1684.

Millennium Ecosystem Assessment, 2005. *Ecosystems and human well-being*. *Washington, DC*.

Miller, C.M., Tsoka, M. & Reichert, K., 2010. Targeting cash to malawi's ultra-poor: A mixed methods evaluation. *Development Policy Review*, 28(4), pp.481–502.

Miller, C.M., Tsoka, M. & Reichert, K., 2011. The impact of the Social Cash Transfer Scheme on food security in Malawi. *Food Policy*, 36(2), pp.230–238.

Misselhorn, A. et al., 2012. A vision for attaining food security. *Current Opinion in Environmental Sustainability*, 4(1), pp.7–17.

Mitchell, M., 1998. *An introduction to genetic algorithms*, MIT press.

Monticino, M. et al., 2007. Coupled human and natural systems: A multi-agent-based approach. *Environmental Modelling and Software*, 22(5), pp.656–663.

Morse, J.M., 1999. Myth #93: Reliability and Validity Are Not Relevant to Qualitative Inquiry. *Qualitative Health Research*, 9(6), pp.717–718.

Moss, S., 2008. Alternative Approaches to the Empirical Validation of Agent- Based Models. *Journal of Artificial Societies and Social Simulation*, 11(15), p.16.

Mouysset, L., Doyen, L., Jiguet, F., Allaire, G. and Leger, F., 2011. Bio economic modeling for a sustainable management of biodiversity in agricultural lands. *Ecological Economics*, *70*(4), pp.617-626.

Müller, B. et al., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software*, 48, pp.37–48.

Müller, B., et al., 2014. Standardised and transparent model descriptions for agent-based models: Current status and prospects. *Environmental Modelling & Software*, 55, pp.156–163.

Murray-Prior, R., 1998. Modelling farmer behaviour: a personal construct theory interpretation of hierarchical decision models. *Agricultural Systems*, 57(4), pp.541–556.

Mwase, N., 2003. The Liberalisation, De-regulation and Privatisation of the Transport Sector in Sub-Saharan Africa: Experiences, Challenges and Opportunities. *Journal of African Economies*, 12(suppl 2), pp.ii153–ii192.

Naivinit, W. et al., 2010. Participatory agent-based modeling and simulation of rice production and labor migrations in Northeast Thailand. *Environmental Modelling and Software*, 25(11), pp.1345–1358.

Nanama, S. & Frongillo, E.A., 2012. Women's rank modifies the relationship between household and women's food insecurity in complex households in northern Burkina Faso. *Food Policy*, 37(3), pp.217–225.

Ndekha, M. et al., 2000. Seasonal variation in the dietary sources of energy for pregnant women in Lungwena, rural Malawi. *Ecology of Food and Nutrition*, 38(6), pp.605–622.

Negin, J. et al., 2009. Integrating a broader notion of food security and gender empowerment into the African Green Revolution. *Food Security*, 1(3), pp.351–360.

Ngure, F.M. et al., 2014. Water, sanitation, and hygiene (WASH), environmental enteropathy, nutrition, and early child development: Making the links. *Annals of the New York Academy of Sciences*, 1308(1), pp.118–128.

Nilson, A. & Piza, J., 1998. Food fortification: a tool for fighting hidden hunger. *Food and Nutrition Bulletin*, 19(1), pp.49–60.

Nin-Pratt, A. & McBride, L., 2014. Agricultural intensification in Ghana: Evaluating the optimist’s case for a Green Revolution. *Food Policy*, 48, pp.153–167.

Nolin, D.A., 2010. Food-sharing networks in Lamalera, Indonesia. *Human Nature*, *21*(3), pp.243-268.

Norström, A. V. et al., 2014. Three necessary conditions for establishing effective Sustainable Development Goals in the Anthropocene. *Ecology and Society*, 19(3).

NSO, 2010. *National Census of Agriculture and Livestock*, Lilongwe.

NSO, 2012a. *Integrated Household Survey 2010/11 (IHS3): NSO*, Lilongwe.

NSO, 2012b. *Intergrated Household Survey (IHS3) Report*, Lilonwe.

NSO, 2015. *Statistical Yearbook*, Lilongwe.

Nyirenda, K. et al., 2000. *Micro-Economic Impact and Willingness to Pay*, Reading.

OECD & FAO, 2015. *Aglink-Cosimo Model Documentation: A partial equilibrium model of world agricultural markets.*, Rome.

Orach, K. & Schlüter, M., 2016. Uncovering the political dimension of social-ecological systems : Contributions from policy process frameworks. *Global Environmental Change*, 40, pp.13–25.

Oreskes, N., Shrader-Frechette, K. & Belitz, K., 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science*, 263(5147), pp.641–646.

Orr, A. & Jere, P., 1999. Identifying smallholder target groups for IPM in southern Malawi. *International Journal of Pest Management*, 45(3), pp.179–187.

Orr, A., Mwale, B. & Saiti-Chitsonga, D., 2009. Exploring Seasonal Poverty Traps : The " Six-Week Window " in Southern Malawi. *The Journal of Development Studies*, 45, pp.227–255.

Orrell, D., 2008. *The future of everything: The science of prediction*, Basic Books.

Parker, D.C. et al., 2003. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers*, 93(2), pp.314–337.

Parunak, H.V.D., Savit, R. & Riolo, R.L., 1998. Multi-agent systems and agent-based simulation. *Proceedings of the First International Workshop of Multi-Agent Systems and Agent-Based Simulation*, pp.10–25.

Patel, R. et al., 2014. Cook, eat, man, woman: understanding the New Alliance for Food Security and Nutrition, nutritionism and its alternatives from Malawi. *The Journal of Peasant Studies*, 42(1), pp.21–44.

Peck, S.L., 2004. Simulation as experiment: A philosophical reassessment for biological modeling. *Trends in Ecology and Evolution*, 19(10), pp.530–534.

Pilkey, O. & Pilkey-Jarvis, L., 2007. *Useless arithmetic: why environmental scientists can't predict the future*, Columbia University Press.

Pimbert, M., 2009. *Towards Food Sovereignty*, London, UK.

Pinstrup-Andersen, P., 2007. Agricultural research and policy for better health and nutrition in developing countries: a food systems approach. *26th Conference of the International Association of Agricultural Economists*, pp.1–27.

Pinstrup-Andersen, P., 2009. Food security : definition and measurement. *Food Security*, 1, pp.5–7.

Poppy, G.M. et al., 2014. Food security in a perfect storm : using the ecosystem services framework to increase understanding Food security in a perfect storm: using the ecosystem services framework to increase understanding. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369, p.20120288.

Porter, G., 2014. Transport Services and Their Impact on Poverty and Growth in Rural Sub-Saharan Africa: A Review of Recent Research and Future Research Needs. *Transport Reviews*, 34(January), pp.25–45.

Potts, D., 2006. Shortages: The Case of Malawi. *Population, Space and Place*, 311, pp.291–311.

Pradhan, P. et al., 2015. Closing Yield Gaps: How Sustainable Can We Be? *Plos One*, 10(6), p.e0129487.

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 363(1491), pp.447–65.

Pretty, J. et al., 2010. The top 100 questions of importance to the future of global agriculture. *International Journal of Agricultural Sustainability*, 8(4), pp.219–236.

Pretty, J., Toulmin, C. & Williams, S., 2011. Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, 9(1), pp.5–24.

Pruyt, E., 2010. Scarcity of Minerals and Metals: A Generic Exploratory System Dynamics Model. *Proceedings of the 28th International Conference of the System Dynamics Society*, *Seoul, Korea, 25-29* (*July 2010*).

Pruyt, E. & Hamarat, C., 2010. The Influenza A(H1N1)v Pandemic: An Exploratory System Dynamics Approach. *Proceedings of the International Conference of the System Dynamics Society*, 2009(April 2009), pp.1–33.

Quinlan, J.R., 1990. Decision trees and decision-making. *Ieee Transactions on Sytems Management and Cybernetics*, 20(2), pp.339–346.

Ramsden, S., Gibbons, J. & Wilson, P., 1999. Impacts of changing relative prices on farm level dairy production in the UK. *Agricultural Systems*, 62(3), pp.201–215.

Rand, W. & Rust, R.T., 2011. Agent-based modeling in marketing: Guidelines for rigor. *International Journal of Research in Marketing*, 28(3), pp.181–193.

Refsgaard, J.C. et al., 2005. Quality assurance in model based water management – review of existing practice and outline of new approaches. *Environmental Modelling & Software*, 20, pp.1201–1215.

Reilly, M. & Willenbockel, D., 2010. Managing uncertainty: a review of food system scenario analysis and modelling. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365(1554), pp.3049–3063.

Ricker-Gilbert, J., Jumbe, C. & Chamberlin, J., 2014. How does population density influence agricultural intensification and productivity? Evidence from Malawi. *Food Policy*, 48, pp.114–

128.

Van Rijn, F., Bulte, E. and Adekunle, A., 2012. Social capital and agricultural innovation in Sub-Saharan Africa. *Agricultural Systems*, *108*, pp.112-122.

Robinson, D.T. et al., 2007. Comparison of empirical methods for building agent-based models in land use science. *Journal of Land Use Science*, 2(1), pp.31–55.

Roncoli, C., Ingram, K. & Kirshen, P., 2002. Reading the Rains: Local Knowledge and Rainfall Forecasting in Burkina Faso. *Society & Natural Resources*, 15(5), pp.409–427.

Rosegrant, M.W. et al., 2014. Global Food Security : Challenges and Policies. *Science*, 1917(2003), pp.10–13.

Rounsevell, M.D. a, Robinson, D.T. & Murray-Rust, D., 2012. From actors to agents in socio-ecological systems models. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 367(1586), pp.259–69.

Ruckelshaus, M. et al., 2013. Notes from the field: Lessons learned from using ecosystem service approaches to inform real-world decisions. *Ecological Economics*, 115, pp.11–21.

Ruel, M.T. & Alderman, H., 2013. Nutrition-sensitive interventions and programmes: How can they help to accelerate progress in improving maternal and child nutrition? *The Lancet*, 382(9891), pp.536–551.

Saad-Filho, A., 2015. Social Policy for Neoliberalism: The Bolsa Familia Programme in Brazil. *Development and Change*, 46(6), pp.1227–1252.

Sabates-Wheeler, R. & Devereux, S., 2013. Sustainable Graduation from Social Protection Programmes. *Development and Change*, 44(4), pp.911–938.

Sahley, C., Groelsema, B., Marchione, T., et al., 2005. *The Governance Dimensions of Food Security in Malawi*, Washington, D.C.

Sahn, D.E. & Arulpragasam, J., 1991. The stagnation of smallholder agriculture in Malawi. A decade of structural adjustment. *Food Policy*, 16(3), pp.219–234.

Sanchez, P. et al., 2007. The African Millenium Villages. *PNAS*, 104(43), pp.6775–16780.

Saqalli, M., 2008. *Populations, Farming systems and Social transitions in Sahelian Niger: An Agent-based Modeling Approach*. University in Ottignies-Louvain-la-Neuve.

Saqalli, M. et al., 2011. Targeting rural development interventions: Empirical agent-based modeling in Nigerien villages. *Agricultural Systems*, 104(4), pp.354–364.

Scheffer, M. & Carpenter, S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology & Evolution*, 18(12), pp.648–656.

Scherpbier, R.W., 2016. China's Progress and Challenges in Improving Child Nutrition. *Biomedical and Environmental Sciences*, 3(29), pp.163–164.

Schilizzi, S.G.M. & Boulier, F., 1997. "Why do farmers do it?" Validating whole-farm models. *Agricultural Systems*, 54(4), pp.477–499.

Schmidhuber, J. & Tubiello, F.N., 2007. Global food security under climate change. *Proceedings of the National Academy of Sciences*, 104(50), p.19703.

Schmolke, A. et al., 2010. Ecological models supporting environmental decision making: a strategy for the future. *Trends in ecology & evolution*, 25(8), pp.479–86.

Schreckenberg, K., 2016. Integrating across disciplines and scales. Presentation to the ESPA Social Surveys Workshop 23rd-24th October.

Schreckenberg, K. et al., 2016. *Participatory Data Collection for Ecosystem Services Research A Practitioner 's Manual*.

Schreinemachers, P. & Berger, T., 2006. Land use decisions in developing countries and their representation in multi-agent systems. *Journal of Land Use Science*, 1(1), pp.29–44.

Schubert, B. & Slater, R., 2006. Social Cash Transfers in Low-Income African countries: Conditional or Unconditiona? *Development Policy Review*, 24(5), pp.571–578.

Schlüter, M. et al., 2007. Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin. *Ecology and Society*, 12(2), p.4.

De Schutter, O., 2014. *Final report: The transformative potential of the right to food*, New York.

Scoones, I., 1998. Sustainable Rural Livelihoods a Framework for Analysis. *IDS Working Paper*, 72, pp.1–22.

Sen, A., 1983. Development: Which Way Now? *The Economic Journal*, 93(372), pp.745–762.

Sen, A., 1990. Gender and cooperative conflict. *Persistent inequalities. Women and world development*, pp.123–149.

Sen, A., 1981. *Poverty and famines: an essay on entitlement and deprivation*, Oxford University

Press.

Senauer, B., 1990. Household behaviour and nutrition in developing countries. *Food Policy*, 15(5), pp.408–417.

Setnes, M., 2001. *Complexity Reduction in Fuzzy Systems*. Delft University of Technology.

Shapiro, A., 2003. Stochastic Programming. *Handbooks in Operations Research and Management Science*, 10, pp.353–425.

De Sherbinin, A. et al., 2009. Rural household demographics, livelihoods and the environment. *Global Environmental Change*, 18(1), pp.38–53.

Shiferaw, B., Prasanna, B.M., Hellin, J. and Bänziger, M., 2011. Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, *3*(3), p.307.

Simon, H., 1955. A Behavioral Model of Rational Choice. *The Quarterly Journal of Economics*, 69(1), pp.99–118.

Simon, H., 1976. *Administrative Behavior, 4th Edition*, Free Press.

Slote, M. & Pettit, P., 1984. Satisficing Consequentialism. *Proceedings of the Aristotelian Society*, 58, pp.139–163.

Smajgl, a. & Bohensky, E., 2013. Behaviour and space in agent-based modelling: Poverty patterns in East Kalimantan, Indonesia. *Environmental Modelling & Software*, 45, pp.8–14.

Smajgl, A., 2010. Challenging beliefs through multi-level participatory modelling in Indonesia. *Environmental Modelling & Software*, 25(11), pp.1470–1476.

Smajgl, A. et al., 2011. Empirical characterisation of agent behaviours in socio-ecological systems. *Environmental Modelling & Software*, 26(7), pp.837–844.

Smith, L.C., Alderman, H. & Aduayom, D., 2007. *Food insecurity in sub-Saharan Africa: new estimates from household expenditure surveys*, Washington: International Food Policy Research Institute.

Smith, L.C. & Subandoro, A., 2007. *Measuring Food Security Using Household Expenditure Surveys*, Washington, D.C.

Sola, P. et al., 2016. Links between energy access and food security in sub Saharan Africa: an exploratory review. *Food Security*, 1, pp.1–8.

Spielman, D.J. et al., 2011. Rural innovation systems and networks: Findings from a study of Ethiopian smallholders. *Agriculture and Human Values*, 28(2), pp.195–212.

Stadlmayr, B. et al., 2012. *West African food composition table*, Rome: FAO.

Sterman, J.D., 2002. All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review*, 18(4), pp.501–531.

Stogartz, S., 2014. *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering*, Westview Press.

Streeten, P., 1980. Basic needs and human rights. *World Development*, 8(2), pp.107–111.

Streeten, P., 1984. Basic needs: Some unsettled questions. *World Development*, 12(9), pp.973–978.

Suckall, N. et al., 2015. Using a migration systems approach to understand the link between climate change and urbanisation in Malawi. *Applied Geography*, 63, pp.244–252.

SUN Movement, 2014a. *An introduction to the Scaling Up Nutrtion Movement*, Available at: http://scalingupnutrition.org/.

SUN Movement, 2014b. Scaling up Nutrition: In Practice Effectively Engaging Multiple Stakeholders., pp.1–44. Available at: http://scalingupnutrition.org/wp-content/uploads/2014/03/Sun-in-Practice-issue-1.pdf.

Swaminathan, H., Salcedo Du Bois, R. & Findeis, J.L., 2010. Impact of Access to Credit on Labor Allocation Patterns in Malawi. *World Development*, 38(4), pp.555–566.

Swindale, A. & Bilinsky, P., 2006. Development of a universally applicable household food insecurity measurement tool: process, current status, and outstanding issues. *The Journal of Nutrition*, 136(5), p.1449S–1452S.

Swindale, A. & Bilnsky, P., 2005. *Household Dietary Diversity Score (HDDS) for Measurement of Household Food Access: Indicator Guide*, Washington, D.C.

Takane, T., 2005. Tobacco and smallholders in Malawi: village case studies in the Mchinji and Mangochi Districts. *African Research Series*, pp.93-119.

Takane, T., 2008. Customary Land Tenure, Inheritance Rules, and Smallholder Farmers in Malawi. *Journal of Southern African Studies*, 34(November), pp.269–291.

Takane, T., 2013. Smallholder livelihoods under economic liberalization in Malawi. *African Journal of Agricultural Research*, *8*(44), pp.5416-5423.

Thangata, P.H., Hildebrand, P.E. & Gladwin, C.H., 2002. Modeling agroforestry adoption and household decision making in Malawi. *African Studies Quarterly*, 6(1-2).

Thiele, J.C., Kurth, W. & Grimm, V., 2012. RNetLogo: An R package for running and exploring individual-based models implemented in NetLogo. *Methods in Ecology and Evolution*, 3(3), pp.480–483.

Thirtle, C., Lin, L. & Piesse, J., 2003. The impact of research-led agricultural productivity growth on poverty reduction in Africa, Asia and Latin America. *World Development*, 31(12), pp.1959–1975.

Thompson, A.M.M. & College, L., 1982. a Farm-Level Model To Evaluate the Impacts of Current Energy Options. Policy Research Report No. 128.

Thompson, J. & Scoones, I., 2009. Addressing the dynamics of agri-food systems: an emerging agenda for social science research. *Environmental Science and Policy*, 12(4), pp.386–397.

Thornton, P.. & Herrero, M., 2001. Integrated crop–livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems*, 70(2-3), pp.581–602.

Thornton, P.K., Jones, P.G., Ericksen, P.J. and Challinor, A.J., 2011. Agriculture and food systems in sub-Saharan Africa in a 4 C+ world. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, *369*(1934), pp.117-136.

Tibesigwa, B., Visser, M., Collinson, M. and Twine, W., 2016. Investigating the sensitivity of household food security to agriculture-related shocks and the implication of social and natural capital. *Sustainability Science*, *11*(2), pp.193-214.

Tidwell, V.C. et al., 2004. System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. *Aquatic Sciences*, 66(4), pp.357–372.

Timmer, C.P., 2010. Reflections on food crises past. *Food Policy*, 35(1), pp.1–11.

Tittonell, P., 2014. Livelihood strategies , resilience and transformability in African agroecosystems. *Agricultural Systems*, 126, pp.3–14.

Tittonell, P. et al., 2009. Beyond resource constraints – Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. *Agricultural Systems*, 101(1-2), pp.1–19.

Todd, J.E., Winters, P.C. & Hertz, T., 2010. Conditional Cash Transfers and Agricultural Production: Lessons from the Oportunidades Experience in Mexico. *Journal of Development Studies*, 46(1), pp.39–67.

Tran, V.T., 2013. Vietnamese economy at the crossroads: New doi moi for sustained growth. *Asian Economic Policy Review*, 8(1), pp.122–143.

UN, 1948. *Universal declaration of human rights*, New York. Available at: http://www.refworld.org/docid/3ae6b3712c.html.

UN, 1974. *Report of the World Food Conference, Rome 5-16 November 1974*, New York.

UN, 1975. *Report of the World Food Conference*, New York. Available at: http://aei.pitt.edu/15701/1/SEC_(74)_4955_final.pdf.

UN, 2001. UN General Assembly. *Road map towards the implementation of the United Nations Millennium Declaration*. Available at: http://www.un.org/documents/ga/docs/56/a56326.pdf.

UN, 2015a. *2015 Revision of World Population Prospects*, New York.

UN, 2015b. Transforming our world: The 2030 agenda for sustainable development.

UN, 2015c. *World Urbanisation Prospects*, New York. Available at: http://esa.un.org/unpd/wup/.

Underwood, B.A., 1998. Perspectives from micronutrient malnutrition elimination/eradication programmes. *Bulletin of the World Health Organization*, 76(Suppl. 2), pp.34–37.

UNDP, 1990. *Human Development Report 1990*, New York. Available at: http://hdr.undp.org/sites/default/files/reports/219/hdr_1990_en_complete_nostats.pdf.

UNDP, 2015. *Human Development Report 2015. Work for Human Development*, New York. Available at: http://hdr.undp.org/sites/all/themes/hdr_theme/country-notes/MEX.pdf.

Valbuena, D., Verburg, P.H. & Bregt, A.K., 2008. A method to define a typology for agent-based analysis in regional land-use research. *Agriculture, Ecosystems & Environment*, 128(1-2), pp.27–36.

Valbuena, D. et al., 2009. An agent-based approach to model land-use change at a regional scale. *Landscape Ecology*, 25(2), pp.185–199.

Valbuena, D. et al., 2014. Improving rural livelihoods as a “moving target”: trajectories of change in smallholder farming systems of Western Kenya. *Regional Environmental Change*, 15(7), pp.1395–1407.

Vargha, A. & Delaney, H.D., 2000. A critique and improvement of the CL common language effect size statistics of McGraw and Wong. *Journal of Educational and Behavioral Statistics*, 25(2), pp.101–132.

Vatn, A. et al., 2006. A methodology for integrated economic and environmental analysis of pollution from agriculture. *Agricultural Systems*, 88(2-3), pp.270–293.

Verburg, P.H. et al., 2015. Methods and approaches to modelling the Anthropocene. *Global Environmental Change*, pp.1–14.

Verduzco-Gallo, I., Ecker, O. & Pauw, K., 2014. *Changes in Food and Nutrition Security in Malawi Analysis of Recent Survey Evidence*, Washington, D.C.

Vizy, E.K. et al., 2015. Projected changes in Malawi's growing season. *Climate Dynamics*, pp.1673–1698.

Van Vuuren, D.P. et al., 2011. The representative concentration pathways: An overview. *Climatic Change*, 109(1), pp.5–31.

Wainwright, J. & Mulligan, M., 2012. Modelling and Model Building. In J. Wainwright & M. Mulligan, eds. *Environmental Modelling: Finding Simplicity in Complexity*.

Waldherr, A. & Wijermans, N., 2013. Communicating Social Simulation Models to Sceptical Minds Common criticism. *Journal of Artificial Societies and Social Simulation*, 16, pp.13.

Wang, W.C., 1998. Fuzzy Logic Toolbox for use with MATLAB. *The MATH WORKS. Berkeley, CA*.

Watts, D.J. & Strogatz, S.H., 1998. Collective dynamics of "small-world" networks. *Nature*, 393(6684), pp.440–2.

Weaver, C.P. et al., 2013. Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, *4*(1), 39-60.

De Weerdt, J. and Dercon, S., 2006. Risk-sharing networks and insurance against illness. *Journal of development Economics*, *81*(2), pp.337-356.

Weichselgartner, J. & Kasperson, R., 2010. Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. *Global Environmental Change*, 20(2), pp.266–277.

Welch, R.M. & Graham, R.D., 1999. A New Paradigm for World Agriculture: Productive, Sustainable and Nutritious Food Systems to Meet Human Needs. *Development Bulletin*, 49, pp.29–32.

White, D.D. et al., 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy*, 37(3), pp.219–232.

Wijk, M.T. Van et al., 2014. Farm household models to analyse food security in a changing climate : A review. *Global Food Security*, 3, pp.77–84.

Van Wijk, M.T. et al., 2014. Farm household models to analyse food security in a changing climate: A review. *Global Food Security*, 3, pp.77–84.

Wilensky, U., 1990. *Netlogo*, Evanston, IL. Available at: http://ccl.northwestern.edu/netlogo/.

Willcock, S. et al., 2016. Do ecosystem service maps and models meet stakeholders' needs? A preliminary survey across sub-Saharan Africa. *Ecosystem Services*, 18, pp.110–117.

Williams, L.J. et al., 2015. Household types as a tool to understand adaptive capacity: case studies from Cambodia, Lao PDR, Bangladesh and India. *Climate and Development*, 5529(October), pp.1–12.

Winsberg, E., 1999. Sanctioning Models: The Epistemology of Simulation. *Science in Context*, 12(02), pp.275–292.

Witten, I.H. & Edibe, F., 2005. *Data Mining: Practical machine learning tools and techniques.*, Morgan Kaufmann.

Wolfram, S. & David, B.L., 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1), p.14010.

Wolfram, S. & Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1), pp.1–8.

World Bank, 1981. *Accelerated development in sub-Saharan Africa, an agenda for action*, Washington, D.C.

World Bank, 2009. *Malawi Public Works Programme Report*, Washington, D.C.

World Bank & IMF, 2013. *Rural-Urban Dynamics and the Millennium Development Goals*, Washington, D.C.

Yang, L. & Gilbert, N., 2008. Getting away from numbers: Using qualitative observation for agent-based modeling. *Advances in Complex Systems*, 11(2), pp.1–11.

Yeung, D.L., 1998. Iron and micronutrients: Complementary food fortification. *Food and Nutrition Bulletin*, 19(2), pp.159–163.

Yücel, G. & van Daalen, C.E., 2011. Exploratory analysis of the impact of information dynamics on innovation diffusion. *Technological Forecasting and Social Change*, 78(2), pp.358–372.

Zadeh, 1965. Fuzzy Sets. *Information and Control*, 8, pp.338–353.

Zadeh, L., 1996. Fuzzy logic equals Computing with words. *Ieee Transactions on Fuzzy Systems*, 4(2), pp.103–111.

Zhao, Y. & Kockelman, K.M., 2002. The Propagation of Uncertainty Through Travel Demand Models: An Exploratory Analysis. *The Annals of Regional Science*, 36, pp.145–163.

Appendices

Appendix A Food items included within the analysis

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Biscuits	Cereals	1	451	2.1	0.6	14	Korkalo et al. (2011)
Bread	Cereals	1	247	0.7	0.76	45	Stadlmayr et al. (2012)
Breakfast cereal	Cereals	1	387	0.5	1.9	3	Estimate
Buns, scones	Cereals	1	264	1.2	0.8	0	Stadlmayr et al. (2012)
Finger millet (mawere)	Cereals	1	348	9.5	1.47	0	Stadlmayr et al. (2012)
Green maize	Cereals	1	349	3.1	1.55	0	Stadlmayr et al. (2012)
Infant feeding cereals	Cereals	1	130	0.1	0.14	3	Stadlmayr et al. (2012)
Maize - boiled or roasted (vendor)	Cereals	1	136	1.3	0.63	17	Stadlmayr et al. (2012)
Maize grain (not as ufa)	Cereals	1	349	3.1	1.55	0	Stadlmayr et al. (2012)
Maize ufa madeya (bran flour)	Cereals	1	351	3.8	1.73	0	Stadlmayr et al. (2012)
Maize ufa mgaiwa (normal flour)	Cereals	1	351	3.8	1.73	0	Stadlmayr et al. (2012)
Maize ufa refined (fine flour)	Cereals	1	354	1.2	1.53	0	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Pearl millet (mchewere)	Cereals	1	364	7.6	2.83	0	Stadlmayr et al. (2012)
Rice	Cereals	1	352	1.9	2.02	0	Stadlmayr et al. (2012)
Sorghum (mapira)	Cereals	1	344	3.7	1.79	1	Stadlmayr et al. (2012)
Spaghetti, macaroni, pasta	Cereals	1	359	1.2	1.41	0	Stadlmayr et al. (2012)
Wheat flour	Cereals	1	351	2	1.8	0	Stadlmayr et al. (2012)
Eggs	Eggs	0.88	139	1.8	1.29	160	Stadlmayr et al. (2012)
Eggs - boiled (vendor)	Eggs	0.88	139	0.88	1.7	152	Stadlmayr et al. (2012)
Dried fish	Fish and seafood	1	255	33.56	6.39	0	Korkalo et al. (2011)
Fish (vendor)	Fish and seafood	1	129	15.65	3.23	0	Estimate
Fish Soup/Sauce	Fish and seafood	0.89	129	15.65	3.23	0	Estimate
Fresh fish	Fish and seafood	1	113	4.28	1.1	10	Korkalo et al. (2011)
Smoked fish	Fish and seafood	1	255	33.56	6.39	0	Korkalo et al. (2011)
Apple	Fruits	0.9	53	0.1	0.04	3	Stadlmayr et al. (2012)
Avocado	Fruits	0.74	154	0.8	0.051	6	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Banana	Fruits	0.64	99	0.3	0.17	4	Stadlmayr et al. (2012)
Citrus – naartje, orange, etc.	Fruits	0.77	47	0.5	0.17	6	Stadlmayr et al. (2012)
Guava	Fruits	0.78	54	0.7	0.32	35	Stadlmayr et al. (2012)
Mango	Fruits	0.71	76	0.7	0.1	168	Stadlmayr et al. (2012)
Papaya	Fruits	0.62	36	0.7	0.12	80	Stadlmayr et al. (2012)
Peach	Fruits	1	39	0.25	0.17	16	Estimate
Pineapple	Fruits	0.51	54	0.5	0.11	5	Stadlmayr et al. (2012)
Watermelon	Fruits	0.56	29	0.3	0.1	42	Stadlmayr et al. (2012)
Wild fruit (masau, malambe, etc.)	Fruits	1	99	0.12	0.13	252	Korkalo et al. (2011)
Beef	Meat, poultry & offal	1	235	2.1	3.6	0	Stadlmayr et al. (2012)
Chicken	Meat, poultry & offal	0.55	107	0.6	0.84	8	Stadlmayr et al. (2012)
Chicken (vendor)	Meat, poultry & offal	0.49	137	0.7	1.07	8	Stadlmayr et al. (2012)
Goat	Meat, poultry & offal	0.74	165	2.4	3.45	0	Stadlmayr et al. (2012)
Meat (vendor)	Meat, poultry & offal	1	343	1.1	2.6	0	Estimate

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Mutton	Meat, poultry & offal	0.75	325	2.1	3.33	10	Stadlmayr et al. (2012)
Other poultry - guinea fowl, doves, etc.	Meat, poultry & offal	0.55	107	0.6	0.84	8	Estimate
Pork	Meat, poultry & offal	1	265	1.4	3.6	0	Stadlmayr et al. (2012)
Small animal – rabbit, mice, etc.	Meat, poultry & offal	0.76	127	1.2	1.7	10	Stadlmayr et al. (2012)
Termites, other insects (eg Ngumbi, caterpillar)	Meat, poultry & offal	1	97	3	3.5	0	Stadlmayr et al. (2012)
Tinned meat or fish	Meat, poultry & offal	1	179	0.83	1.66	0	Korkalo et al. (2011)
Butter	Milk and milk products	1	720	0.03	0.12	696	Stadlmayr et al. (2012)
Cheese	Milk and milk products	1	396	0.8	3.78	265	Stadlmayr et al. (2012)
Condensed Milk	Milk and milk products	1	328	0.2	0.94	74	Stadlmayr et al. (2012)
Fresh milk	Milk and milk products	1	65	0.05	0.39	33	Stadlmayr et al. (2012)
Infant feeding formula (for bottle)	Milk and milk products	1	519	9.3	3.9	467	Stadlmayr et al. (2012)
Margarine - Blue band	Milk and milk products	1	730	0.1	0	819	Stadlmayr et al. (2012)
Powdered milk	Milk and milk products	1	495	0.7	3.51	228	Stadlmayr et al. (2012)
Yoghurt	Milk and milk products	1	73	0.1	0.58	30	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Bottled / canned beer (Carlsberg, etc.)	Miscellaneous	1	35	0.1	0.01	0	Stadlmayr et al. (2012)
Bottled water	Miscellaneous	1	0	0	0.01	0	Stadlmayr et al. (2012)
Chibuku (commercial traditional-style beer)	Miscellaneous	1	43	0.2	0.14	0	Stadlmayr et al. (2012)
Cocoa, millo	Miscellaneous	1	115	0.89	0.26	5	Estimate
Coffee	Miscellaneous	1	2	0	0.08	1	Stadlmayr et al. (2012)
Freezes (flavoured ice)	Miscellaneous	1	77.4	0	0	0	Estimate
Fruit juice	Miscellaneous	1	44	0.3	0.05	8	Stadlmayr et al. (2012)
Hot sauce (Nali, etc.)	Miscellaneous	1	104	0.8	0.16	34	Estimate
Jam, jelly	Miscellaneous	1	280	0.49	0.06	0	Korkalo et al. (2011)
Locally brewed liquor (kachasu)	Miscellaneous	1	34	0.5	0	0	Stadlmayr et al. (2012)
Maheu	Miscellaneous	1	43	0.2	0.14	0	Stadlmayr et al. (2012)
Mandazi, doughnut (vendor)	Miscellaneous	1	316	0.6	0.4	0	Stadlmayr et al. (2012)
Salt	Miscellaneous	1	0	1.2	0.1	0	Stadlmayr et al. (2012)
Samosa (vendor)	Miscellaneous	1	280	1	1.5	0	Estimate

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Soft drinks (Coca-cola, Fanta, Sprite, etc.)	Miscellaneous	1	39	0.11	0.02	0	Korkalo et al. (2011)
Spices	Miscellaneous	1	348	7.1	1.01	27	Stadlmayr et al. (2012)
Squash (Sobo drink concentrate)	Miscellaneous	1	57	0.18	0.03	38	Korkalo et al. (2011)
Sweets, candy, chocolates	Miscellaneous	1	400	0.3	0.01	0	Korkalo et al. (2011)
Tea	Miscellaneous	1	0	0.1	0.03	0	Stadlmayr et al. (2012)
Thobwa	Miscellaneous	1	43	0.2	0.14	0	Stadlmayr et al. (2012)
Tomato sauce (bottle)	Miscellaneous	1	101	0.35	0.17	26	Estimate
Traditional beer (masese)	Miscellaneous	1	43	0.2	0.14	0	Stadlmayr et al. (2012)
Wine or commercial liquor	Miscellaneous	1	34	0.5	0	0	Stadlmayr et al. (2012)
Yeast, baking powder, bicarbonate of soda	Miscellaneous	1	315	20	8	0	Stadlmayr et al. (2012)
Cooking oil	Oils and fats	1	900	0	0	0	Stadlmayr et al. (2012)
Bean, brown	Pulses, legumes & nuts	1	335	5.7	3.77	15	Stadlmayr et al. (2012)
Bean, white	Pulses, legumes & nuts	1	335	5.7	3.77	15	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Cowpea (khobwe)	Pulses, legumes & nuts	1	316	7.3	4.61	3	Stadlmayr et al. (2012)
Ground bean (nzama)	Pulses, legumes & nuts	1	335	5.7	3.77	15	Stadlmayr et al. (2012)
Groundnut	Pulses, legumes & nuts	1	578	3.9	2.5	0	Stadlmayr et al. (2012)
Groundnut flour	Pulses, legumes & nuts	1	586	4	2.6	0	Stadlmayr et al. (2012)
Macademia nuts	Pulses, legumes & nuts	1	589	3.7	2.9	0	Estimate
Pigeonpea (nandolo)	Pulses, legumes & nuts	1	301	4.7	1.96	1	Stadlmayr et al. (2012)
Soyabean flour	Pulses, legumes & nuts	1	410	7.8	4.73	1	Stadlmayr et al. (2012)
Cassava - boiled (vendor)	Roots and tubers	1	161	0.7	0.32	1	Stadlmayr et al. (2012)
Cassava flour	Roots and tubers	1	335	1.5	0.74	0	Stadlmayr et al. (2012)
Cassava tubers	Roots and tubers	0.84	153	0.7	0.34	1	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Chips (vendor)	Roots and tubers	1	546	2	0.7	0	Korkalo et al. (2011)
Cocoyam (masimbi)	Roots and tubers	0.81	129	0.6	0.36	0	Stadlmayr et al. (2012)
Irish potato	Roots and tubers	0.84	80	0.9	0.35	1	Stadlmayr et al. (2012)
Orange sweet potato	Roots and tubers	0.84	112	1.1	0.39	397	Stadlmayr et al. (2012)
Plantain, cooking banana	Roots and tubers	0.65	593	0.9	0.12	43	Stadlmayr et al. (2012)
Potato crisps	Roots and tubers	1	546	2	0.7	0	Korkalo et al. (2011)
White sweet potato	Roots and tubers	0.84	115	1	0.35	3	Stadlmayr et al. (2012)
Sugar	Sugar and honey	1	400	0.1	0.01	0	Stadlmayr et al. (2012)
Sugar Cane	Sugar and honey	1	56	0.9	0	0	Korkalo et al. (2011)
Bonongwe (thorny amaranth)	Vegetables	0.94	39	6.2	0.72	241	Stadlmayr et al. (2012)
Cabbage	Vegetables	0.8	115	0.6	0.2	8	Stadlmayr et al. (2012)
Chinese cabbage	Vegetables	0.8	115	0.6	0.2	8	Stadlmayr et al. (2012)
Cucumber	Vegetables	0.81	15	0.5	0.17	3	Stadlmayr et al. (2012)
Eggplant	Vegetables	0.81	125	0.9	0.14	3	Stadlmayr et al. (2012)

Cont.

Item name	Food group	Edible portion per 100g	Energy (kcal)	Iron (mg)	Zinc (mg)	Vitamin A (µg RAE)	Source
Gathered wild green leaves	Vegetables	1	47	4.74	0.49	267	Korkalo et al. (2011)
Moringa (Sangowa)	Vegetables	0.8	86	6.1	0.9	738	Stadlmayr et al. (2012)
Mushroom	Vegetables	1	27	0.5	0.52	0	(Korkalo et al. 2011)
Nkhwani (pumpkin leaves)	Vegetables	0.41	27	2.2	0.2	192	Stadlmayr et al. (2012)
Okra / Therere	Vegetables	0.86	33	0.8	0.6	26	Stadlmayr et al. (2012)
Onion	Vegetables	0.91	37	0.3	0.26	0	Stadlmayr et al. (2012)
Other cultivated green leafy vegetables	Vegetables	1	47	4.74	0.49	267	Korkalo et al. (2011)
Peas (nsawawa)	Vegetables	1	74	1.7	0.87	0	Stadlmayr et al. (2012)
Pumpkin	Vegetables	0.7	29	1.2	0.32	100	Stadlmayr et al. (2012)
Soyabeans	Vegetables	1	410	7.3	4.61	3	Stadlmayr et al. (2012)
Tanaposi/Rape	Vegetables	0.87	78	2.25	0.88	63.6	Estimate
Tinned vegetables (Specify)	Vegetables	1	83	0.8	0.2	22	Stadlmayr et al. (2012)
Tomato	Vegetables	0.91	22	0.6	0.7	52	Stadlmayr et al. (2012)

Appendix B Model Details

B.1 Initialisation

This section outlines the model initialisation process. All initialisation data are read from text files at the beginning of each simulation.

B.1.1 Initialisation of Households and Individuals.

To represent a hypothetical village within Southern Malawi, data corresponding to 116 unique households is drawn from a sample of the IHS3 dataset (n=2492). The same sample set was used to construct the initial household typology (Dobbie *et al*., in review). For each household a number of attributes are drawn from the survey data. These include: household size, household type (farmer, agricultural labourer or non-agricultural worker) financial capital and livestock. Attributes of individuals corresponding to the selected households are also initialized using survey data. Gender, age, education level, household status and health of individuals are drawn from the IHS3 dataset. A total of 546 individuals are initialised. A summary of attribute values at initialisation can be found in Table B.1.

B.1.2 Initialisation of the environment.

Attributes of farm plots and dimba patches corresponding to each of the households are also taken from the sampled IHS3 dataset. These include patch area in addition to past allocations of crop types and applications of inputs in the form of pesticides and inorganic fertiliser. The IHS3 does not contain village level data on the area of cropland, water and forest. Instead analysis of land cover data from Masdap (www.masdap.mw/) and GlobCover 9 (http://due.esrin.esa.int/page_globcover.php) enabled the area of cropland, water and forest to be approximated for 7121 rural villages within Southern Malawi. The average proportions of different land types present within each village were then calculated. Typically village land cover comprised of 31.6 % cropland, 67.8 % forest and 0.7 % water. This was used to generate values for areas of forest and water, based upon the total amount of farmland owned by the sampled households (n=166).

Table B.1: Summary of attribute variables at initialisation for households, individuals and agricultural land.

Attribute	Full Sample		Farmers		Agricultural Labourers		Non-agricultural workers	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Households								
n	116		73		15		28	
Household size	4.7	2.2	4.7	2.3	5.1	2.1	4.4	2.0
Financial capital (USD)	10.7	37.9	13.6	40.7	8.0	38.0	4.4	29.6
No. of cattle	0.1	0.3	0.1	0.5	0	0	0	0
No. of poultry	2.4	4.9	2.1	4.1	1.4	2.5	3.8	7.1
Individuals								
n	546		346		76		124	
Age	21.7	19.8	22.1	20.2	22.6	19.9	20.3	18.5
Education level	0.48	0.60	0.45	0.63	0.45	0.50	0.49	0.58
Agricultural land								
n	98		62		10		26	
No. of farm plots owned	1.9	1.1	2	1.1	1.5	0.8	1.8	1.1
No. of dimba plots owned	0.1	0.3	0.1	0.4	0	0	0	0.2
Total area of land owned (ha)	0.54	0.45	0.57	0.47	0.32	0.29	0.57	0.44

B.2 Input data

B.2.1 Climate data.

Climate variability is represented by annual rainfall. At the beginning of each model year, a value is drawn from a list of rainfall data. This list was generated using MarkSim, a third-order Markov rainfall generator that can be employed as a Global Climate Model (GCM) downscaler (Jones & Thornton 2013). Daily rainfall projections for Malawi were generated from 2010 to 2050. This was based upon the average output of 17 GCM's using the RCP2.6 scenario, as defined by the IPCC (Van Vuuren et al. 2011). Daily values were then aggregated to give an estimate of annual rainfall (See Fig. C.5).

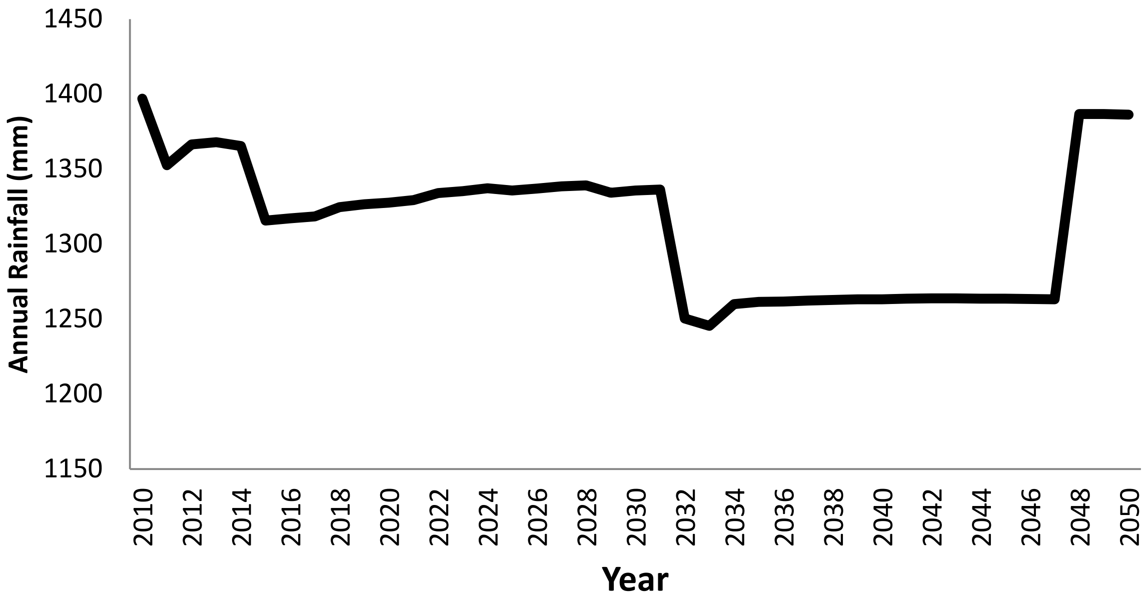

Figure B.1: Annual rainfall projections for Malawi generated using MarkSim (Jones & Thornton 2013).

B.2.2 Population growth.

Village-level population growth was approximated using rural population projections from the 2014 revision of world urbanisation prospects (UN 2015c). As projections consider the number of individuals only, the growth in household numbers at the village level had to be estimated. This was achieved using the simple equation:

hh = rpop * prop / hhsize (C.2)

where *hh* is the number of households, *rpop* are the rural population projections (UN 2015c), *prop* is the proportion of rural individuals living in Southern Malawi and *hh-size* is the average size of households (based on census data for 1987, 1988 and 2008) (See Fig. C.6). In order to simulate population growth, at the end of each model year, the number of new households to be created is read from a list. Households and individuals are created and initialized accordingly, drawing upon data from IHS3. In order to allocate patches, each new household asks a member of its social network to spare their smallest patch of fallow land. Patches may also be split. This reflects the matrilineal nature of customary land tenure in Malawi (Takane 2008). It should be noted however, that for this model version, household demographics have been simplified considerably. Neither households nor individuals age over time. Instead, new households are simply added at the end of each agricultural season and existing households continue with the same attributes as before.

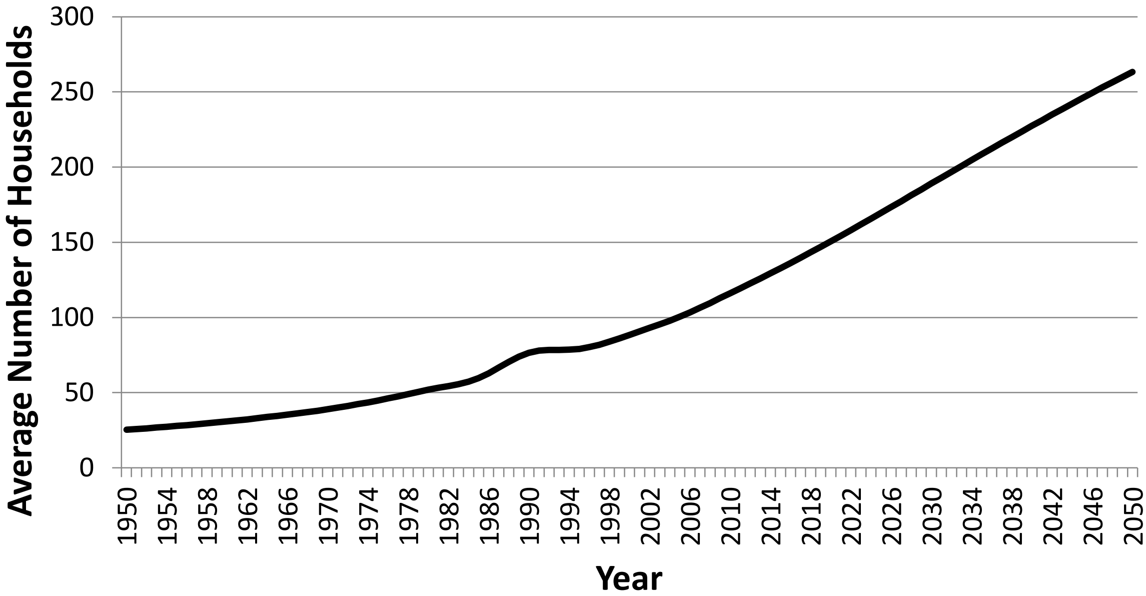

Figure B.2: Population projections for rural Southern Malawi based upon UN (2015). Average numbers of households per village are given.

B.2.3 Markets.

The local market prices for 11 food categories are provided as inputs to the agent-based model at initialization. The model stores the annual market price of these commodities starting at 2010 for the following 40 years. The market value of crops and livestock products such as milk, eggs and meat play an important role within the model. Changes over time are simulated using two well established global models: AGLINK-COSIMO (OECD & FAO 2015) and GCAM4.0 (Kyle et al. 2011; Capellán-pérez et al. 2014). AGLINK-COSIMO is a recursive-dynamic, partial equilibrium model used to simulate developments of annual market balances and prices for the main agricultural commodities produced, consumed and traded worldwide. GCAM is a dynamic recursive economic partial-equilibrium model driven by assumptions about population size and labour productivity that determine potential gross domestic product in market exchange rates in 14 geopolitical regions. It combines representations of the global economy, energy systems, agriculture and land use, with a representation of terrestrial and ocean carbon cycles and a suite of coupled gas-cycle, climate, and ice-melt models.

The first 4 years (2010 to 2014) are based upon empirical data. The value is expressed in USD/kg, using reference values from either IHS3 (NSO, 2012), or the World Food Programme database of market prices (http://foodprices.vam.wfp.org/Default.aspx), according to data availability. For the following years we apply to the baseline value of 2014, the percentage price change provided by the models described above. This is an important assumption that allows us to override the local inflation and currency exchange rate. From 2015 to 2025, we applied the annual percentage price change provided by the AGLINK-COSIMO model. As the model does not simulate national prices for Malawi, average values associated with three neighbouring countries: Tanzania, Zambia and Mozambique, are taken. From 2025 on, trends were applied from the simulated global prices of GCAM4.0 assuming the representative concentration pathway (RCP) 2.6 as the climate change scenario (Van Vuuren et al. 2011) and the absence of carbon taxation on CO_2 from land-use changes. As this model produces simulated prices at 5 year intervals, we split the aggregate 5 year changes uniformly to generate annual price changes.