Smallholder Food Security Impacts of Industrial Crop Expansion and Land Use Change in Malawi: A System Dynamics Simulation

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Declaration

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Abstract

Food security is still a pervasive problem, nowhere more so than in sub-Saharan Africa (SSA). Industrial crop (IC) expansion has been at the centre of a debate as to whether ICs are assisting or hindering the quest for a more food secure future. These conflicting views, outlined in a review of pertinent literature, highlight the need for further study into the topic. A review of the literature revealed that food security in the context of SSA is a complex issue and a function of integrated social, economic, and physical systems. To understand this complex system better, it is proposed that a computer-based model is constructed to simulate the dynamics of the system. Models that simulate food security or food security related issues were therefore reviewed and the absence of a simulation that modelled food security from the household level perspective was uncovered. Various modelling attributes and techniques were subsequently reviewed, and system dynamics was chosen as the most appropriate modelling methodology to tackle the research problem under consideration in this study. The software package Vensim was selected as the modelling medium. For the development of the model, Malawi was identified as a suitable country to serve as the case study for this research inquiry. A conceptual model was created explaining the system feedbacks observed in Malawi through causal loop diagrams. The formal simulation was then developed from the conceptual model.

It was found that the cultivation of ICs contribute to food security in Malawi. This is largely the result of increased credit options available to smallholder farmers who engage in IC cultivation. Smallholders who cultivate multiple crops are generally more food secure than those who monocrop in cases where limited land is available. This is because mixed-crop farmers are less vulnerable to climate variability. In some cases, mixed cropping leads to staggered income sources and expenses, this reduces the amount of time between harvests and leads to briefer episodes of food shortages overall. Cassava, a plant resilient to extreme weather conditions, is an important food crop in combatting food insecurity. Tobacco, a high-value crop which is well suited to climatic conditions in much of Malawi, remains a lucrative option for smallholder farmers. Contractual agreements between leaf companies, sugar millers, and smallholder farmers could, however, be improved. It is recommended that a regional-level model is developed to capture the effects of higher level system dynamics on smallholder farmers to be used in conjunction with this model.

Keywords: food security; industrial crops; computer modelling; Malawi; system dynamics

Opsomming

Voedselsekuriteit is steeds 'n algemene probleem, veral in sub-Sahara Afrika (SSA). Uitbreiding van industriële gewasse (IG) was die middelpunt van 'n debat wat gehandel het oor die vraag of IGs die soeke na 'n veiliger toekoms vir voedsel kan bevorder of verhinder. Hierdie teenstrydige standpunte, soos uiteengesit in 'n oorsig van toepaslike literatuur, beklemtoon die behoefte aan verdere studies wat handel oor hierdie onderwerp. 'n Hersiening van die literatuur het getoon dat voedselsekuriteit in die konteks van SSA 'n komplekse kwessie is, en 'n funksie van geïntegreerde sosiale-, ekonomiese- en fisiesestelsels is. Om hierdie komplekse stelsel beter te verstaan, word voorgestel dat 'n rekenaargebaseerde model ontwikkel word om die dinamika van die stelsel te simuleer. Modelle wat voedselsekuriteit of voedselsekuriteits verwante kwessies simuleer, is hersien en die afwesigheid van 'n simulasie wat voedselversekering en voedselsekuriteit vanuit die huishoudelike-vlak perspektief modelleer, is ontbloot. Verskeie modelleringseienskappe en -tegnieke is hersien, en stelseldinamika is gekies as die toepaslike modelleringsmetodologie. Die sagtewarepakket Vensim is gekies as die modelleringsmedium. Vir die ontwikkeling van die model is Malawi as geskikte land geïdentifiseer om as gevallestudie vir hierdie navorsingsondersoek te dien. 'n Konseptuelemodel is geskep wat die stelsel terugvoering wat in Malawi waargeneem word, deur middel van oorsaaklike lusdiagram, verduidelik. Die formele simulasie is dan uit die konseptuele model ontwikkel.

Daar is bevind dat die verbouing van IGs bydra tot voedselsekuriteit in Malawi. Dit is hoofsaaklik as gevolg van die groter hoeveelheid kredietopsies wat beskikbaar is vir kleinhoewe-boere wat betrokke is by IG-verbouing. Kleinhoewe-boere wat veelvuldige gewasse verbou, is meer voedselveilig as diegene wat slegs enkele gewasse verbou in gevalle waar beperkte grond beskikbaar is. Die rede hiervoor is omdat boere wat gemengde-gewas boerderye bedryf minder vatbaar vir klimaatsverandering is. In sommige gevalle lei gemengde gewasverbouing tot gesteierde inkomstebronne en uitgawes, wat gevolglik die inkomstegaping tussen oeste verminder en ook lei tot korter voedseltekort episodes. Cassava, 'n plant wat veerkragtig is vir uiterste weerstoestande, word beskou as 'n belangrike voedselgewas in die bestryding van voedselonsekerheid. Tabak, 'n hoë waarde-oes wat goed by die klimaatstoestande in Malawi pas, bly 'n winsgewende opsie vir kleinboere. Kontrakooreenkomste tussen blaarmaatskappye, suikermolers en kleinboere kan egter verbeter word. Daar word aanbeveel dat 'n streeksvlakmodel ontwikkel word om die effekte van hoërvlak-stelseldinamika op kleinboere te verstaan en dat so ‘n hoë-vlak model gebruik word saam met die model wat in hierdie studie ontwikkel is.

Sleutelwoorde: voedselsekuriteit; industriëlegewasse; rekenaarmodellering; Malawi; stelseldinamika

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List of Abbreviations

ARET	Agricultural Research and Extension Trust
BEFS	Bioenergy and Food Security Projects
CGE	Computable General Equilibrium
CGM	Cassava green mite
CIP	International Potato Centre
CLD	Causal loop diagram
CLUE	Conversion of Land Use and its Effects
CM	Cassava mealybug
CMV	Cassava mosaic virus
CSIR	Council for Scientific and Industrial Research
DCGL	Dwangwa Cane Growers Limited
DCGT	Dwangwa Cane Growers Trust
DER	Dietary energy requirement
DWASCO	Dwangwa Sugar Corporation
EBA	Everything but arms
EIU	Economist Intelligence Unit
EU	European Union
FACCE-JPI	Joint Programming Initiative on Agriculture, Food Security and Climate Change
FAO	Food and Agricultural Organisation of the United Nations
FEWS NET	Famine Early Warning Systems Network
FICESSA	Food security impacts of industrial crop expansion in Sub-Saharan Africa
GDP	Gross domestic product
GOM	Government of Malawi
IC	Industrial crop
IPC	The Integrated Food Security Phase Classification

IPS	Integrated Production System
JTI	Japan Tobacco International
LDC	Least developed country
LSC	Lonrho Sugar Corporation
MCDA	Multi-criteria decision analysis
MOP	Muriate of Potash
MRA	Malawi Revenue Authority
MWK	Malawian Kwacha
NSO	National Statistical Office of Malawi
ODI	Overseas Development Institute
SD	System dynamics
SODA	Strategic options development and analysis
SPVD	Sweet potato virus disease
SSA	Smallholder Sugar Authority
SSA	Sub-Saharan Africa
SUCOMA	Sugar Corporation of Malawi
TA	Traditional authority
TAMA	Tobacco Association of Malawi
TCC	Tobacco Control Commission
UN	United Nations
UNU	United Nations University
ZAR	South African Rand

Chapter 1: Introduction

This chapter aims to provide a brief introduction to the study as well as provide relevant contextual information regarding the study's setting in the greater issue of food security and land-use change in the nation of Malawi. The chapter will highlight food security as a complex issue and introduces the idea of applying systems thinking and computer-based simulation as a means to understand it. The issues are described in the problem statement and the study's research objectives are outlined. Finally, this chapter highlights the research approach followed by the study in order to achieve the study objectives.

1.1 A study in context: Food security, land-use change, Malawi

This study forms part of a greater research effort which aims to determine the effects of industrial crop expansion in Sub-Saharan Africa. FICESSA - Food security impacts of Industrial Crop Expansion in Sub-Saharan Africa - is a three-year interdisciplinary project that aims to provide clear empirical evidence of how industrial crops (ICs) compete with food crops for land and other productive resources and explain the mechanisms through which this competition affects food security (Gasparatos, Locke, Von Maltitz, Willis & Takeuchi, 2013). The study has been approved and funded by the Belmont Forum and Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI). The interdisciplinary team is comprised of scientists, researchers, and students from The University of Tokyo, Royal Botanic Gardens Kew, the Overseas Development Institute (ODI), the Council for Scientific and Industrial Research (CSIR), and the United Nations University (UNU). The project consists of eight interlinked work packages (WPs). This study contributes to work package four (WP4).

Food security is by no means a new issue, however, even sixteen years after world leaders set out to eradicate poverty and extreme hunger through the implementation of the millennium development goals (MDGs) these are still pervasive issues. It is thought that over 800 million people still suffer from hunger and are unable to meet their daily dietary energy requirements (DER). This means that worldwide 1 in 9 people goes to bed on an empty stomach (FAO 2014). Food security, as defined by the World Food Summit (1996),

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"exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."

The concept of food security was first introduced in the 1970's and the World Food Conference of 1974 was one of the first to attempt defining the new term. The past thirty years have seen a multitude of attempts to capture the essence of food security into a single definition (FAO, 2006) and it is quite plain that the concept of food security will continue to evolve in order to further capture its varied meanings to different people. The meaning of food security in the Malawian perspective is unique and this study explores how food security is best defined in the context of this study, to provide a basis for meaningful modelling and simulation outputs.

Malawi is one such country, like many others in sub-Saharan Africa, which has more than its fair share of hungry people. Malawi is a small landlocked country in south-eastern Africa – see **Figure 1.1** - with an estimated population of 18 million people (World Bank, 2016). Malawi lies wholly within the tropics; however, the climate is sub-tropical, regulated by the altitude, and is strongly seasonal (Malawi Meteorological Services, 2006). The climate is hot in the low lying southern areas and temperate in the highlands of northern Malawi. Rainfall occurs during the warm summer months and the average annual rainfall varies between 725mm and 2500mm depending on location. Around 95% of the annual precipitation falls during the warm wet season from November to April. The winter season is cool and dry and runs from May until August where frost is uncommon. Malawi's landscape is arguably dominated by Lake Malawi (also called Lake Nyasa). The lake is 587km long, 84km wide and up to 701m deep. It provides an almost limitless supply of fresh water. Despite this, less than 5% of Malawi's renewable water resources are withdrawn annually (Leete, Damen & Rossi, 2013).

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Figure 1.1*: Malawi in Southern Africa* ("LocationMalawi.png", 2014)

Malawi is characterized by a very high dependence on agriculture (FAO Commodities and Trade Division, 2003) with over 85% of Malawian households reporting engagement in agricultural activities (NSO, 2012). Agriculture accounts for 30% of Malawi's GDP and over 90% of the country's export earnings (Corporate Citizenship, 2014). Malawian agriculture is comprised of both small-scale farmers and large estates. Smallholder farming is largely subsistence-based with over 80% of smallholder farmers cultivating less than 2 hectares of land. Despite smallholder farming being defined by low levels of input and output, it accounts for around 80% of Malawi's food production and contributes to about 20% of agricultural exports.

Maize is the largest food crop both in terms of production and dedicated acreage. It is reported to account for roughly 50% of the total calories consumed by the population, however, recent efforts at diversification have led to a significant increase in the production of potatoes and cassava (Leete *et al.*, 2013). Tobacco is Malawi's most important cash crop and principal foreign exchange earner. It accounts for over 50% of exports making Malawi the world's most tobacco-dependent economy (Drope, Makoka, Lencucha & Appau, 2016). Sugar and tea are Malawi's next biggest exports.

Malawi is classified as a Least Developed Country (LDC) according to the United Nations (UN) (2017) with low levels of literacy and life expectancy. Only 9% of Malawians have access to electricity and for rural Malawi, this number is closer to 1% (Leete *et al.*, 2013). Biomass accounts for 90% of fuel energy consumption and has led to widespread deforestation as rural households cut down trees to meet the demand for wood fuel.

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The World Bank listed Malawi as the world's second poorest country (for which data exists) in 2016 based on the gross domestic product (GDP) per capita. Malawi's most recent Integrated Household Survey (IHS3) conducted by the National Statistical Office (NSO) reported that 50.7 percent of Malawi's population lives on or below the poverty line (NSO, 2012). The poverty line is calculated as the cost of a food bundle that provides the necessary daily dietary energy requirements (DER), in this case, chosen as a minimum of 2400 kilocalories per person per day. Thus, those living below the poverty line would be unable to sustain the minimum daily DER required and would suffer from undernourishment and undernutrition. It is important to note here that the poverty line calculated by the NSO is far lower than the global poverty line of US$2 per day. More than 80% of Malawians live under the global poverty line according to the Economist Intelligence Unit (EIU) (2014).

Poverty in Malawi is highest in rural areas (Meerman, Aberman, Harris & Pauw, 2015) and the introduction of high-value cash crops or biofuel feedstocks – collectively referred to as industrial crops - has been proposed as a pathway to reducing poverty and thereby increasing food security. Understandably, the growing of crops on arable land that do not contribute to food supplies in some of the world's least developed countries has also prompted concern (Wiggins, Henley & Keats, 2015). Concern that the displacement of food production could lead to lower supply, higher food prices, and leave farmers overexposed to market risks.

There is much debate about what effect industrial crops (ICs) have on food security and whether they can be used to uplift and develop areas with poor communities or instead result in the further marginalisation of these people. The debate first raged in the form of the 'food vs fuel' debate, however, this can be misleading as the issues raised by both sides are also true for many other non-food and cash crops, which will collectively be termed industrial crops. There is no simple answer as to whether the introduction and adoption of ICs are ultimately beneficial or detrimental to local, regional, or national economies. At the local scale, it is largely accepted that ICs compete both directly and indirectly for land with food crops, however, a number of less obvious mechanisms may lead to improvements in local food security (Gasparatos *et al.*, 2013). At larger scales, implications for regional or national food security is likely to be negligible if expansion is limited to a few projects that comprise only a small percentage of total arable land. However, for those involved in the projects their personal food security situation could be dramatically altered. This is food security at the household level.

If IC expansion is more substantial and comprises of the conversion of large tracts of land and a significant share of the agricultural labour force then food prices, trade, employment opportunities, development, and other macroeconomic variables will be affected, all of which might in turn affect food security in either a positive or negative manner. The presence of many different drivers and variables across the social, economic and environmental spheres, many of which are endogenous to the IC-food security system, mean that this study falls in the realm of complex systems. A system which is not the sum of its parts but rather a product of the interaction of its parts (Maani & Cavana, 2007). Systems thinking is a scientific field of knowledge for understanding change and complexity through the study of dynamic cause and effect over time (Maani & Cavana, 2007). This study will show how systems thinking is necessary to tackle complex issues of this nature and furthermore, show how systems thinking methodology, including problem structuring, causal loop modelling, and dynamic simulation, might be applied in an effort to distinguish causes from symptoms when it comes to the issue of food security in sub-Saharan Africa.

This study aims to explore the role of IC expansion within the broader issue of food security by providing a discussion of various concepts and important terminology, a review of the appropriate literature regarding food security, land-use change, and various possible modelling methodologies as well as computer simulation mediums. Finally, the study aims to create a fully executable dynamic computer-based simulation to capture the various physical, economic, and social impacts of IC expansion on food security in the Malawian perspective.

1.2 Research rationale

This locale of research is important for several reasons. Firstly, as briefly outlined in section 1.1, the present state of food security in Malawi is dire. High rates of stunting and wasting among children, and low life expectancy are but a few immediate indicators of the need for increased attention to the plight of Malawian smallholder farmers. The increased pressure on the agricultural sector to solve both the issues of poverty and food insecurity necessitates the introduction and implementation of good policy. A policy that is based on sound scientific understanding. However, it is not only policy-makers that are tasked with making important decisions. Good economic and agricultural decisions must also be made at the household-level if families are to step out of poverty and into a future that is more food secure. Research aimed at providing information that can support both household-level decision-making and regional and national policymakers is therefore important.

Additional pressure is placed on the agricultural sector as the world seeks to find an alternative, cleaner source of fuel. Biofuel is one avenue for cleaner ‘greener’ energy. Land conversion to biofuel feedstocks has been encouraged and often financed through direct foreign investment (Negash & Swinnen, 2013). This has led to the redeployment of large tracts of land in SSA in countries, that are already largely food insecure, away from the production of food. Malawi produces large quantities of ethanol for mixture with traditional fuels for use in the transport sector (Leete *et al.*, 2013). The widespread cultivation of cash crops is another response from Malawi's agricultural sector to achieve economic growth. As discussed, this resulted in Malawi becoming the world's most tobacco-dependent country as it pursued the promises of green gold.

The effects of both cash crops and biofuel feedstocks on food security in Malawi are unclear and so too are the possible effects of future endeavours. Furthermore, while the effects of both cash crops and biofuel feedstocks on food security have been explored individually to some degree, their combined effect – the effect of industrial crops - of these two interlinked systems has not been studied sufficiently, especially at the household-level.

This combination of factors; Malawi's state of food security, the pressure on the agricultural sector to deal with poverty and food insecurity through cash crops, exogenous pressure to cultivate biofuel feedstocks in search of clean energy, the presence of interlinking actors and variables forming complex systems and the lack of research in this field all reveal the need for further research into this locale of study.

1.3 Problem statement

There is an undesired pattern of recurring food insecurity in Malawi. It is the result of the country's interlinked social, political, economic, and agricultural systems. Actors and variables within these systems interact with each other to form multiple feedback loops. The effect that industrial crops have within these loops is unclear. The mapping and computer-based simulation of these feedback loops will lead to a better understanding of Malawi's systemic structures upon which steps can be taken to address not merely the symptoms of the problem but rather the causes of the problem.

1.4 Research question

The research question is formulated as a response to the problem statement. The question aims to capture the essence of the problem in a single question that will form a basis for the formulation of the research objectives. The research question is,

What effect does the cultivation of industrial crops have on household food security in Malawi?

The overarching goal of this research is two-pronged, and as such two primary-level objectives have been formulated,

i) The first is a comprehensive study of the relevant literature in order to explore concepts of interest to this study, the context in which it takes place, the complex nature of the study, and the different methodological and computer-based approaches that have been or might be used as tool to address the problem outlined in the problem statement.

ii) The second is the development of a dynamic systems-based computer simulation that models existing feedback loops in Malawi's agricultural and socio-economic systems, those systems pertaining to food security, industrial crops and land use change, which provides meaningful outputs in the quest for a problem solution.

1.5 Research objectives

With the two primary objectives established this section serves to provide clear secondary objectives that are necessary for dividing the primary objectives into distinct conquerable tasks. The first primary-level objective pertains mostly to a study of existing literature and can be deconstructed into the following secondary objectives:

i) To investigate the context and setting in which the research and case study will take place to serve as both a grounding for the study's development and as an introduction for a reader that is unfamiliar with either the studies subject matter, context, or both.

ii) To investigate the concept and measurement techniques of food security in the literature to determine a definition of food security that is both measurable and meaningful to smallholder farmers in Malawi.

iii) To explore the benefits and show the need for the creation and application of a computer-based model for dealing with the problem as outlined by the problem statement through the study of the literature.

iv) To identify and explain generic modelling attributes applicable to various modelling techniques to provide context for the eventual selection of the model type and form.

v) To review current models and modelling techniques in use for modelling the impacts of industrial crops and land-use change on food security.

vi) To review different modelling methodologies and mediums available for the development of a computer-based simulation.

vii) To show through the literature Malawi's merit as an ideal case study for the focus of this research and to investigate and present information pertaining to Malawi's agricultural sector and the crops that will be included in the process of model development.

The second primary level objective concerns the creative and developmental process and the application of the created work to the real world. It also requires the following of the regimented methodology of the chosen modelling procedure, in this case, the system dynamics framework. The second primary-level objective is partitioned into the following secondary objectives:

i) To structure the problem according to the systems thinking and modelling (ST&M) methodology by defining the issue and identifying the scope and boundaries of the study.

ii) To develop a conceptual model of the problem through the creation of causal loop diagrams (CLDs) in order to identify key variables and illustrate the relationships between the variables.

iii) To develop the dynamic model in the form of a computer simulation based on the conceptual model which includes stocks, flows, and converters utilising the specialised computer package Vensim by Ventana Systems.

iv) To determine the baseline and develop the scenarios of various policies and strategies to be run by the dynamic computer-based model.

v) To run the model, capture, and discuss the results of the model from which stakeholder recommendations and concluding remarks shall be formulated.

1.6 Outline of research

The following is provided as a summary of the research approach and aims to inform the reader of the structure of this paper.

Chapter	***Title & description***
Chapter 1	**Introduction** Chapter one presents the context in which the study takes place and provides signposts for the research to come.
Chapter 2	**Review of literature** Chapter two provides the methodology followed in the review of the literature and aims to provide a review of pertinent concepts, modelling techniques, and relevant models.
Chapter 3	**Model development**

	Chapter three follows methodology according to the systems thinking and modelling process, where the conceptual and dynamic models are constructed, and various scenarios are formulated.
Chapter 4	**Results and analysis** In chapter four the outcomes and results of the various scenarios run by the model are presented and discussed.
Chapter 5	**Conclusion and recommendations** The final chapter of the study summarises the study's findings and provides recommendations to both policymakers and smallholder farmers based on the results. The study's limitations and opportunities for future study are provided here.

1.7 Conclusion

Chapter one introduced the concepts of food security, industrial crops, land-use change, and the problem as a complex system. It provides a background on the Malawian context in which this study takes place and explains why Malawi serves as an excellent locale for the basis of this case study. Information regarding the importance of research on this topic is provided and the problem statement is developed. From this, the research question is formulated, and both the primary and secondary-level objectives are stated. Finally, the research outline of the study is provided. The following chapter is primarily concerned with an analysis of the available literature pertinent to the study's domain of interest.

Chapter 2: Review of literature

This chapter serves to examine the important concepts relevant to the study with regard to their meaning and definition in the context of this study. The chapter progresses to explain, through the literature, the possible benefits of applying a computer-based simulation to the issue. A variety of model attributes are then explored. The chapter will examine, and review modelling methods and techniques applied to the issues of land-use change and food security that already exist in the literature. Different modelling mediums will be investigated. Finally, relevant literature pertaining to Malawi's agricultural sector will be provided owing to the importance of crop cultivation to the livelihoods of smallholder farmers in Malawi. Information pertaining to crops selected for inclusion in the simulated model is provided, information used to populate one of the model's sub-models.

2.1 Literature analysis methodology

A systematic search of scholarly articles was undertaken by searching for those containing a combination of four keywords, "food security," "industrial crops," "Sub-Saharan Africa," and "modelling." No articles were found to contain all four keywords and the search was expanded by substituting "Malawi" and "Africa" for "Sub-Saharan Africa," and substituting "industrial crops" with "cash crops," "food vs fuel" (and derivatives including biofuels, fuel crops, biodiesel and bioethanol), and individual crop names such as sugar, tobacco, groundnuts, cotton etc. The returned journal articles, reports, and books were then compared and contrasted in search of the various arguments both for and against the idea that industrial crops are complimentary to food security. Next, a review of food security and food system related case studies was undertaken without limiting the scope to the African perspective. Case studies containing a reference to "modelling," "system dynamics," and "simulation" were selected for review. A review of various modelling techniques was undertaken where the focus was on the potential inclusion of qualitative data and soft systems modelling, however, it quickly became clear that the priority was the discovery of a hard-modelling technique instead, that had mixed data handling abilities. Finally, literature pertaining to the growth, life cycles, and farming practices of sugarcane, tobacco, maize, cassava, and potatoes in Malawi was reviewed. This literature was supported by literature pertaining to Malawi's immediate neighbours, those countries that share a land border with Malawi.

2.2 Objectives of the review of literature

The objective of this review of literature is fourfold:

- i) To provide context to the food security issues that plague Malawi and the conflicting views over the role that industrial crops (ICs) play in the greater food security system.
- ii) To bring meaning and definition to these concepts in the context of this study.
- iii) To highlight the need for superior policy decisions to be made to alleviate the current food security condition.
- iv) To identify knowledge gaps and show the need for a computer-based model in order to understand and find solutions in a complex system.
- v) To review and analyse various modelling techniques to determine the modelling technique and methodology best suited to model the socio-agricultural system at hand.
- vi) To provide information relevant to Malawi's smallholder agrarian society, the primary system under investigation in this study, information that will be used in the construction of a computer based model.

2.3 Defining food security

The definition of food security has evolved over the years (Renzaho & Mellor, 2010). The most widely accepted definition has become that which was formulated in the Rome Declaration on World Food Security which defines food security as "when 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" (World Food Summit, 1996). This definition, however, requires further definitions as to what might be considered nutritious enough food or what is meant by food preferences (Renzaho & Mellor, 2010). This definition would, therefore, lump someone who might have a minor iron deficiency with another on the verge of starvation and brand them both as food insecure. Clearly, in the interest of providing help to those who need it most further distinctions must be made within this concept of food security.

According to the Food and Agriculture Organisaton of the United Nations (2014), malnutrition comes in three forms; caloric undernourishment, micronutrient deficiency (undernutrition), and obesity. All three must be combatted in order to meet the FAO standards of food security. Certainly, in many African countries, there exist families that suffer from the triple burden of malnutrition (Gómez, Barrett, Raney, Pinstrup-Andersen, Meerman, *et al.*, 2013), where within the same household, some members of the family are suffering from extreme hunger while others are obese. Obesity seems paradoxical to food insecurity and so one might ask why it is included. One major cause of obesity is naturally the consumption of too much food, or more specifically too many calories. There are, however, links between both undernourishment and nutrient deficiency with obesity (Dietz, 1995). Whether periods of prolonged hunger lead to a psychological tendency to binge eat or to physical reactions within the body to store fat upon food availability, it seems that obesity is not independent of either not having enough food (undernourishment) or healthy food (undernutrition) with regards to food security. Therefore, the root cause of obesity, where it is concerned with food insecurity issues, is in the other two forms of malnutrition.

It is proposed that only undernourishment and undernutrition need be considered with regard to causation and that obesity is instead considered as an indicator of potentially underlying food insecurity issues such as undernourishment and undernutrition. Food security is, therefore, a function of both undernourishment and undernutrition. This concept is outlined in **Figure 2.1**.

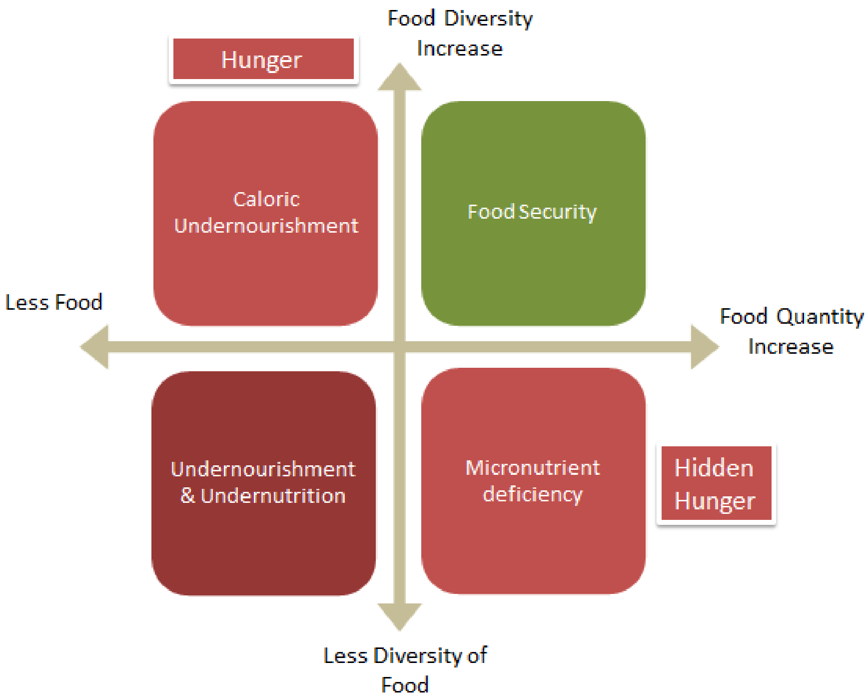

Figure 2.1: *Defining Food Security*

Lack of food and associated caloric undernourishment leads to hunger. According to the FAO (2014) over 800 million people cannot meet their daily dietary energy requirements (DER). Hidden hunger is a term that alludes to micronutrient deficiencies (undernutrition) and is thought to affect almost 2 billion people worldwide (Jones, Ngure, Pelto & Young, 2013). It is important to remember that there is significant overlap between these two groups and it is likely that most who are suffering from hunger are suffering from hidden hunger as well. In reality, there are probably comparably few people who exist in the top left quadrant of the food security matrix where one has a micronutrient sufficiency but simultaneously cannot meet one's DER. Therefore, it is proposed that a progression from food insecurity into a state of food security would generally follow a path that moves first right, and then upwards, beginning from the bottom left quadrant. This is synonymous with, first, an increase in quantity and then an increase in quality or diversity of food. Thus, potentially the first challenge to overcoming food insecurity, and this might be labelled as step 1, is that of addressing caloric undernourishment; what is traditionally known as hunger.

This study will thus be chiefly concerned with food insecurity as it refers to hunger and caloric insufficiency whereby people cannot meet their DER because of food shortages.

2.4 Measuring food security

Measuring food security, something difficult just to define, is even more difficult. It is widely recognised that food security is comprised of 4 pillars; that of access, availability, utilisation, and stability (Renzaho & Mellor, 2010). Access refers to both the affordability and allocation of food to a household or within a region. Availability refers to supply and if there is enough food on the market for everyone. Utilisation refers to the safety and quality of the food and often extends to incorporate the effects of sanitation and access to potable water. Stability refers to the fact that crop cycles, weather patterns, the open market, and even the effects of politics and war are ever changing, and all directly or indirectly affect regional or national food security. A lack of stability can lead to short-term food insecurity (seasonal) or long-term food insecurity (chronic).

While the abstract concept of food security is difficult to measure, its constituents; access, availability, utilisation and stability, might be scaled using food security indicators. Historically, measuring food security relied solely on measuring undernourishment, however; this is but one manifestation of food insecurity FAO (2014). Only measuring undernourishment has drawbacks, for example, a child whose anthropometric measurements are considered normal (i.e. they are neither stunted nor wasted) could be suffering from anaemia and not receiving the nutrients necessary for a healthy and active life. Furthermore, a child's anthropometric measurements might be considered normal as the result of recent years of good rains and plentiful harvests, but a lack of irrigation in the region could mean that same child would suffer heavily if the rains failed in the following season. With this in mind, it is easy to see that this child does not have ironclad assuredness of access to and availability of food whatever his anthropometric measurements might be. This shows how the use of only a single indicator might be misleading when it comes to measuring food security (Maxwell & Smith, 1992). In fact, the inability of a single indicator to measure the comprehensiveness of the definition of food security has raised questions to whether the concept should be disaggregated into its component definitions in order to adequately capture varying degrees of severity (Jones *et al.*, 2013).

New approaches, such as that adopted by the Economist Intelligence Unit (EIU), attempt to measure a wide range of indicators (Economist Intelligence Unit, 2014) and the FAO's report 'Food Security in Numbers' (2014) provides an extensive list of indicators that range from measuring rail densities through to the political stability of an area. While many of these indicators are wholly quantifiable, some are based on a rating system and are thus considered qualitative. The inclusion of qualitative indicators has successfully provided a much clearer picture of the food security situation.

It is important to remember that there is a difference between measuring food security and modelling food security. This is because a measurement is static while the food security system, that which is modelled, is dynamic (Christos, Naoum & Dimitrios, 2014). Many of the so-called food security models might more aptly be described as food security measurement models which are different from food security system models. However, many of the indicators suggested for food security measurement might also have use in a food security system model. Many of these indicators also have limitations as to where and how they can be used.

There is no doubt that using multiple indicators is helpful to gauge the level of food security within a region (Jones *et al.*, 2013) but there are two primary drawbacks of using food security indicators to understand food security. The first issue is that many indicators describe food security through correlation and not causality. The second issue is that many indicators, especially those that are qualitative, are not fit for use in a hard, quantitative, modelling approach.

2.4.1 Moving from correlation to causality

Food security is a complex issue. Effective steps cannot be taken to rectify complex issues unless the system is adequately understood and the cause, not symptoms, of the problem identified (Maani & Cavana, 2007). Although these indicators provide more complete pictures of food security situations, indicators by their very nature are indicative of the state of food security in an area. While many of these indicators might well be causes of food security in their own right, many indicators do not directly contribute towards food insecurity, or at least not principally. Thus, for a factor to be labelled a food security indicator, it is correlation and not causality between the indicator and food security that needs to be established. However, if policy decisions need to be made with the aim of improving food security one must derive policy to influence factors that have been identified as primary causes of food insecurity and not just factors that correlate with food security. Thus, a computer model that begins to explore the underlying causes of food insecurity would add increased value to our understanding of the food security system.

2.4.2 Moving from static measurement to dynamic modelling

The EIU (2015) model uses a variety of indicators that are useful for food security measurement, but they are not dynamic in nature. Here, these indicators are used to describe food security within a region at a particular time. Models that use these indicators can answer a question such as “What is the state of food security in Malawi now?” What they struggle to answer is “What will the state of food security be 5 years from now?”

To answer this question, a time-based simulation model needs to be constructed, one that can run a variety of potential scenarios and determine food security outputs (Muetzelfeldt, 2010). However, many food security indicators, in particular, those that are qualitative, cannot be used in a dynamic simulation where mathematical relationships between variables must be established. In models that describe the state of food security at a particular time, food security is eventually expressed as a weighted sum of its constituents, however; the relationships that exist between constituents are not defined. In reality, there exist feedbacks between the constituents in the system and a model that can begin to map these relationships would prove far more insightful. This model would move beyond displaying the state of food security and begin to provide insight and understanding into the dynamics of the food security system. There is a knowledge gap with regard to dynamic models that measure food security in this way.

2.5 Modelling food security

The meaning, definition, and measurement of food security has been dealt with in the previous sections; now the modelling of food security will be investigated and discussed. In the following section, the reasons for modelling food security will be examined, the various attributes important to models of land-use change and food security will be discussed, and finally models that model land-use change and food security that exist in the literature will be reviewed.

2.5.1.1 Why model food security?

Before discussing the various approaches and methods used to model food security and related issues it is important to answer the question as to why food security should be modelled at all and what benefits can be gained from the modelling procedure and outputs. At its core food security is a developmental problem. Developmental problems are frequently recognized as pre-existing conditions in need of change such as poverty, poor governance, inadequate infrastructure, technological backwardness, low productivity, and food shortage (Saeed, 2003). To begin drafting policy to address the issue one needs to start with recognition of the poor current state of affairs. At this point developmental policy is then constructed to improve the existing conditions but, despite good intentions, Saeed (2003) argues that experience shows that this often leads to unexpected results and unreliable policy performance. This is the result of the causes of the existing condition and their future projections not being properly understood. This leads to policy that addresses the symptoms of the problem and not the cause where ad hoc changes are superseded by system reactions. Saeed (2003) proposes that development planning must adopt a problem-solving approach in a mathematical sense. This is analogous to forming a real understanding of the underlying causes of a delineated pattern.

Thompson & Scoones (2009) emphasize that agri-food systems are embedded in complex ecological, economic and social processes and are dynamic and vulnerable to both short-term shocks as well as long-term stresses. They also highlight the need for the deeper understanding of 'rural worlds' in particular and how these communities might achieve sustainability through agriculture. Muetzelfeldt (2010) also stresses that dealing with food security and its associated agricultural, environmental, social, and economic subsystems is complex and poses significant challenges in representing the current state of knowledge as well as exploring how these systems might evolve over time in response to external drivers and human input. Furthermore, the behaviour needs to be explained and displayed in a manner that is meaningful to stakeholders and policymakers involved. Finally, Lambin et al. (2000) argue that an integrated approach to modelling is likely to best serve the objective of improving the understanding of land-use change processes. Lambin et al. (2000) suggest that the ability to model decision-making processes within the system might even be more important than the broad category of model used. Lambin et al. (2000) also show the importance of scenario analysis in conjunction with model development given the impossibility of specific predictions in complex systems of this nature.

It is in the context of these complex systems that a computer-based simulation model is necessary. This is shown to have the advantages of helping to understand the underlying causes that lead to developmental problems, forecasting future projections of current trends in a system that can respond unexpectedly to external shocks, aiding policy development that addresses problem causes and not symptoms, showing decision making processes explicitly, displaying system behaviour to stakeholders meaningfully, and incorporating scenario analysis to answer various what-if questions that may arise through the modelling process.

2.5.2 Review of modelling attributes

Before one can review the different models that exist in the literature, one must understand what options are available to the modeller in the model building process. There are a variety of model attributes that distinguish one model from the next. When choosing model attributes, it is important to keep the problem statement and study objectives in mind to ensure model attributes are chosen that produce a model that best serves the studies objectives. Those attributes most important to food security and land use change models are discussed below.

Verburg *et al.* (2004) suggest that the first model attribute one needs to consider is the **level of analysis.** Here the modeller needs to decide between the micro and macro level perspective. An approach from the micro-level perspective models the behaviour of individuals or the smallest entity (parcel) of a system and upscale this behaviour to determine higher-level trends or patterns (Bell & Irwin, 2002). Multi-agent simulation and microeconomic models are examples of modelling approaches from the micro-level perspective. Most current multi-agent models can only simulate very simplified landscapes as the number of factors and interacting agents in food security and land use change models are too large to make comprehensive multi-agent models. Micro-economic models are centred on the idea that individual landowners will make land use decisions based on the desire to maximise land utility and land returns. As the name suggests, economic theory is used to guide model development. Pure micro-economic models have a history of upscaling issues as they have been designed to work at the micro level (Verburg, Schot, *et al.*, 2004).

McGregor, Rola-Rubzen and Murray-Prior (2001) note that the specificity of micro-level studies is both its strength and weakness. The primary advantage of micro-level modelling is that the scale corresponds to the scale at which economic or agricultural land use decisions are made by those responsible for decision making (Bell & Irwin, 2002). While micro-level models can provide insights into the intricacies of the physical, economic, and environmental systems and their interactions their micro-nature can lead to a lack of applicability for policy analysis. McGregor, Rola-Rubzen and Murray-Prior (2001) maintain that the outputs from micro-level analyses are important prerequisites for macro-level analysis. Certainly, this is supported by Bell and Irwin (2002) who argue that an understanding of the determinants of land use change requires an understanding of individual decision making at the parcel level.

Macro-level perspective modelling estimates system determinants at the aggregate or county level (Bell & Irwin, 2002). Macro-level perspective models are based on macroeconomic theory or apply the systems approach. Computable general equilibrium models are an example of macro-level perspective models. Other macro-level perspective models are based on spatial structure analysis where model behaviour is not linked to the behaviour of individuals but rather to the spatial structure of land use (Verburg, Schot, *et al.*, 2004). While land use change is the result of many independent decisions made by individual land users the consequences of land use change are often realised at more aggregate scales (Bell & Irwin, 2002).

Cross-scale dynamics is the second attribute that needs to be considered. Scale has already been discussed in part where the **level of analysis** of a model is highlighted. Scale refers to the spatial, temporal, quantitative, or analytic dimension chosen for the model (Verburg, Schot, *et al.*, 2004). Scales are defined by extent and resolution. Extent refers to the total magnitude of the items or area to be included in the model and Brooks and Tobias (1996) refer to this as the scope of a model. Resolution refers to the precision or smallest entity of measurement of the model and this is referred to as the level of detail by Brooks and Tobias (1996). For example, in a spatial model, the total map area included in the model would be the extent and the smallest single grid area on that map modelled as a single entity would be the model resolution. For an economic, agent-based, or systems model, the extent might be the region or the total number of households modelled. Deciding on a model resolution would be a choice between modelling communities, households, or individuals as the smallest single entity being modelled.

Systems can be organised at different levels. Organisational levels include organism (individual), ecosystem, regional, national and global levels (Verburg, Schot, *et al.*, 2004). Feedbacks occur between agents and/or processes from different levels, however, most land use models are solely based on one scale or level. The resolution used in the analysis is often a result of the measurement technique, available data or where predictability is highest. Naturally, studies that cover a large spatial extent or sizable population group will have a coarser resolution. Large extent and coarse resolution models lose the ability to track certain features that are observable in case studies of smaller extent and finer resolution which exude greater detail. The converse is also true, where scales of smaller extent and finer resolution often lack important contextual information and perspective that is achieved by models with a broader scope (Verburg, Schot, *et al.*, 2004).

Another attribute important when choosing the model type and build style is that of **driving forces.** Ecological and social systems are linked through the idea that humans respond to events in both the physical and sociocultural environment (Verburg, de Nijs, van Eck, Visser & de Jong, 2004). Modelling land use change and food security requires the selection of those socioeconomic and biophysical driving forces that are thought to be most significant to measured outcomes. Whether these driving forces are exogenous or endogenous to the system and whether to model these driving forces endogenously or exogenously is an important decision faced by the modeller. The model's temporal scale of analysis is crucial when making this decision. Driving forces might be considered exogenous to models over short time horizons but endogenous to model dynamics over a significant amount of time (Maani & Cavana, 2007).

There are three methods available for determining the relationships between driving forces and land use change and food security identified by Verburg, Schot, *et al.* (2004). The first method is where model processes and variable relationships are defined by mathematical theory and physical laws. This approach has encountered challenges for integrated land-use change modelling where it can be difficult to include socioeconomic variables without the use of empirical data. Thus, the second approach makes use of empirical analysis to quantify the relationships between driving forces, land use change and food security. Empirical analysis employs statistical techniques, most commonly regression, based on historical data in order to construct meaningful relationships. A disadvantage of statistical analysis, as noted by Verburg, Schot, *et al.* (2004), is the element of uncertainty with regard to the causality between the hypothetical relations. The third method used to quantify the relationships between driving forces and the variables that they influence is that of expert knowledge.

Another attribute to consider before the modelling medium is chosen is the extent of **spatial interaction and neighbourhood effects.** Some degree of autocorrelation is present in nearly all land use patterns (Verburg, Schot, *et al.*, 2004). Autocorrelation is the tendency of random variables taking values in pairs based on their physical distance apart (spatial autocorrelation) or distance apart in time (temporal autocorrelation). This correlation is positive as pairs exhibit more similar values and negative when they exhibit values or properties less similar than expected for randomly associated pairs of observations (Legendre, 1993). The presence of autocorrelation is largely explained by environmental conditions, but further explanation can be found in the spatial interactions between the different land use types. For example, an influencing factor in a smallholder farmer switching from maize cultivation to sugar production might be the fact that many of his neighbours are growing sugar. This is known as neighbourhood effects.

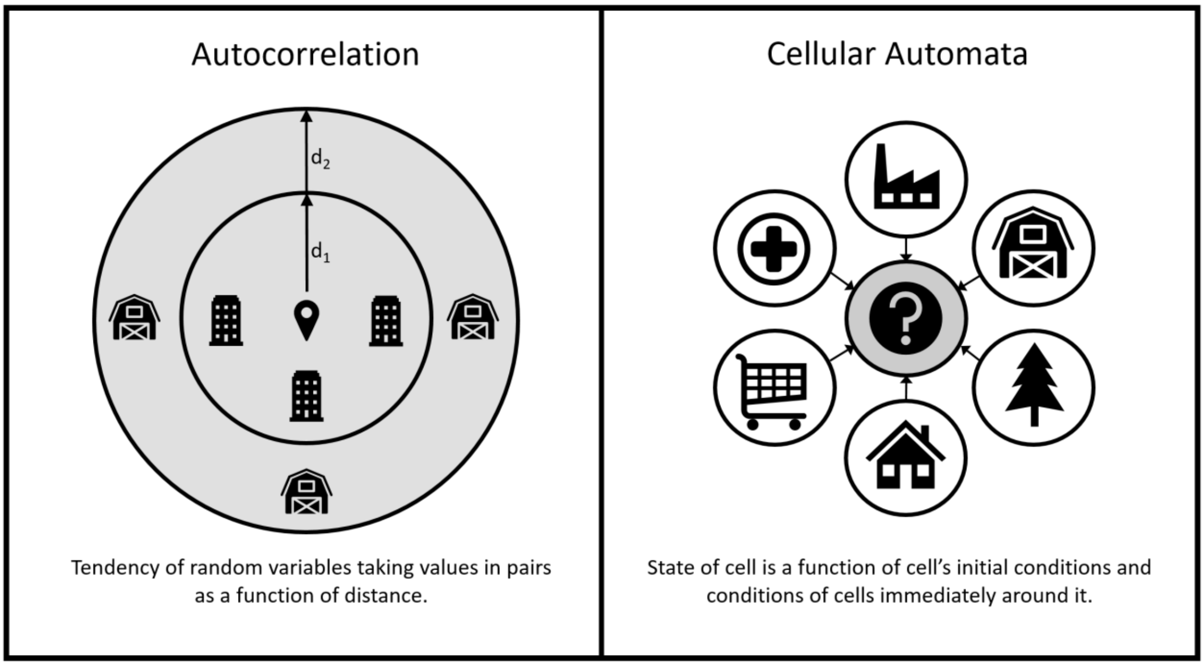

Figure 2.2: *Describing Autocorrelation and Cellular Automata*

Cellular automata are one method of modelling spatial interactions. Cellular automata calculate the state of one pixel based on its initial conditions and the conditions of the pixels immediately around it i.e. those pixels in its neighbourhood (Kari, 2005) (Zaitsev, 2017). Neighbourhood characteristics are more commonly being used in econometric models. In some cases, advanced methods of autocorrelation are used in econometric models, however, more often simpler measures are used. Including the area of a land-use type as an explanatory variable in regression models is an example of a simpler method (Verburg, Schot, *et al.*, 2004). Other models have used network analysis to incorporate spatial interaction and neighbourhood effects. This is primarily used in modelling spatial interactions over large distances. In most cases, network analysis uses simple measures such as the travel time, distance, or cost and use the results to explain land usage.

Many of the previous attributes discussed dealt with the spatial characteristics of land use change. The **temporal dynamics** of the system to be modelled need to be accounted for and a decision made whether the model will attempt to include the temporal dimension. Changes in land use and its effect on food security are often non-linear. This non-linear behaviour demands dynamic modelling with small time steps. Verburg, Schot, *et al.* (2004) argue only then can land-use change analysis begin to account for path dependency as its own driving force in the evolution of a system. Most generally, path dependency is defined by the notion that history matters (Liebowitz & Margolis, 1999). This means that a system's end or future state is not only dependent on initial conditions but also on any accidental or random events (noise) that occur along a time series.

These events, which often seem trivial, can have a lasting and often irreversible impact on the state of equilibrium ultimately reached. This implies that there exist multiple stable states that any single system might achieve, and the final state reached is dependent on the path the system takes to get there in addition to the initial conditions. Only dynamic modelling can account for the possibility of multiple trajectories (Verburg, Schot, *et al.*, 2004).

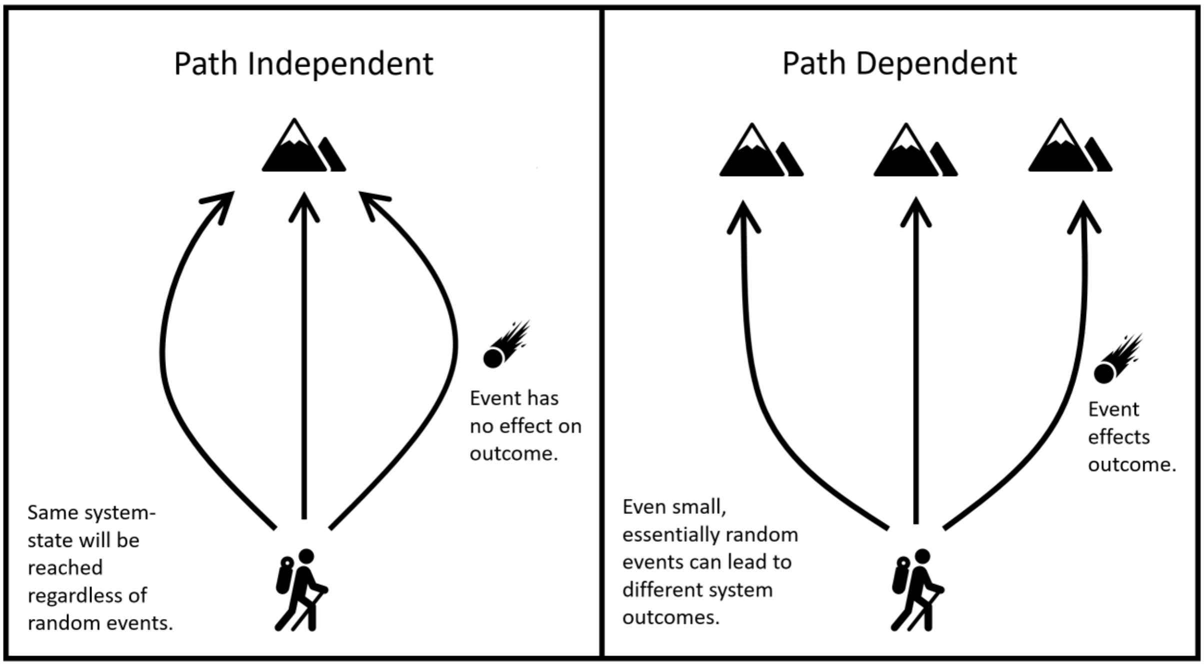

Figure 2.3: *Explaining Path Dependency*

Temporal dynamics raises the issue of model validation. Validation of models dealing with land use change is often grounded on the comparison of a model's results using historical data with the actual observations of change in land-use as they occurred (Verburg, Schot, *et al.*, 2004) (Pontius, Cornell & Hall, 2001). This requires model data for a second year. Ideally, the time difference between the two years should be equal to or longer than the intended duration of the model scenario run time to allow for a real comparison of the simulated versus actual system dynamics. This historical data can be difficult to attain and in many cases data from different time periods are not easily compared owing to different methods of data classification (Pontius *et al.*, 2001). Models that do not take temporal dynamics into account are not suitable for scenario analysis. The combination of both temporal and spatial dynamics can lead to complex non-linear behaviour.

Finally, one needs to consider the model's level of **integration**. Integrated models are those that attempt to portray the social, economic, environmental, and institutional dimensions of problem or system (Rotmans & Asselt, 2001). Food security and land use systems are characterised by non-linear interactions and feedback loops. These make causes and effects difficult to identify from one another especially in the presence of delays and limits (Costanza, Wainger, Folke & Mäler, 1993). This complexity makes the integration of multiple subsystems within the larger system one of the most crucial aspects of land use and food security model development (Verburg, Schot, *et al.*, 2004). Verburg *et al.* (2004) propose that there are two approaches for integration and that these are distinguished by the level of integration each of them utilizes. The first approach is one where subsystems are analysed and modelled separately but remain loosely coupled. Here, one assumes that the interactions and feedbacks between variables across the two subsystems are negligible or that relationships between the subsystems is clearly defined and can be passed through the exchange of input and output variables. In the second approach, the attention is shifted from subsystem descriptions to subsystem interactions. This approach means more variables are endogenous to the system and are dependent on both intra and inter-system dynamics. Verburg *et al.* (2004) caution that the number of interactions identifiable in food security and land use systems is very large and attempting to account for all of these can lead to models becoming too complex to be operational.

Most integrated assessment models are directed to the modelling of climate change and the potential impact of national and global policy (Verburg, Schot, *et al.*, 2004). There exist integrated assessment models that contain land use models but these are often very simple in comparison to models that are purely designed for land use studies. Rotmans and Asselt (2001) conclude that the same conclusion is true for both integrated assessment models and land use models, that many large models exist that consist of linked subsystems that are not fully integrated. This means that, while they might be complicated, they are not complex, having behaviour that is almost linear which is not properly representative of real-world dynamics.

2.5.3 Review of current models

The difficulty of defining and measuring food security naturally lend themselves to issues in model construction. This broad definition combined with the various techniques to measure food security means that the avenues for modelling food security are seemingly endless. When deciding how to model food security it is important to have a good understanding of the problem at hand. From this, the problem definition can be constructed. One can then select the type, features and attributes, and the medium for model construction that is best suited to the problem at hand as outlined by the problem definition.

Because the problem definition of this particular study seeks to determine the effect of land use change on food security, when considering the model type and form, those features of models that belong to both pure food security models and pure land use change models will be considered. However, in truth, it could be argued that any food security model that doesn't consider land usage to at least some degree might be incomplete.

A few papers explore how particular modelling techniques might be applied to food security, some of which go on to create conceptual models. There are fewer papers still that actually apply full computer-based simulation to food security.

The Integrated Food Security Phase Classification (IPC) is a set of tools and processes to analyse and classify the severity of food insecurity in a particular region according to a common standard (IPC, 2017). With reference to the IPC brochure, classification essentially acts as a thermometer that gauges the temperature of the state of food security at a given time. This is much like other 'snapshot' food security models where the results only reflect the present state; however, the IPC also takes two more important steps. Firstly, it aims to identify the causes that lead to food insecure situations. Secondly, although the IPC classification is undertaken to describe the food security situation at the time of the analysis, the IPC also includes vulnerability factors in order to predict the possible evolution of the food security situation (IPC, 2017). This is used in an attempt to classify the future risk of a worsening situation according to the most likely scenario. The model, however, is still only applied for one particular instance, and the vulnerability factors are used to say whether the situation is likely to improve or deteriorate over a chosen period of time. This is very useful but is still fundamentally different to a model that returns outputs for incremental periods of time. Furthermore, the IPC is a framework and not a computer simulated model. Therefore, although it can be updated as new data becomes available, it is not dynamic and reclassification is needed if new data are incorporated. It uses various food security indicators, such as mortality and food consumption levels to classify the prevailing food security situation according to five phases; minimal, stressed, crises, emergency, and famine.

The Famine Early Warning Systems Network (FEWS NET) is one such food security model that provides much more than just a snapshot. FEWS NET aims to provide early warning of acute food insecurity and impending famine. It is similar to the IPC in the sense that it actually uses the IPC to determine the classification of the food security situation of a certain place. However, instead of running the model for the present time and then forecasting with the use of vulnerability factors like the IPC, FEWS NET uses scenario development to determine the most likely model inputs at a future point in time and then applies these probable future parameters to the IPC framework in order to obtain the forecast (Hillbruner, 2012).

CHAPTER 2: REVIEW OF LITERATURE

Scenario development is a methodological tool for forecasting future events. Essentially scenario development is an if-then statement that gains rigour through analysis (Hillbruner, 2012). The FEWS NET scenario development relies on the creation of specific, informed assumptions about future events, their effects on a population group, and then the likely responses the various actors are capable of (Hillbruner, 2012). This is then submitted through the IPC classification system which is used to describe the food security state of the particular demographic or by area. The use of scenario development to aid in the adjudication of what impact a particular shock might have on a population group gives FEWS NET extra credibility when it comes to food security forecasts and this makes FEWS NET invaluable as a tool for predicting potential food crises. One major benefit of scenario development is that the process can be followed in order to gauge the effect of a very specific shock to a people group or area. For example, this could be useful in this study to consider how the introduction of industrial crops might affect food security levels for a certain area in Malawi.

There are limitations to this method. FEWS NET makes assumptions to predict events and more importantly, makes assumptions on how these events might affect household food security. The assumptions are created by studying historical data, similar cases, and consulting expert opinion (Hillbruner, 2012). In the case of Malawi, when answering questions such as how food production or income might change over time, these answers must be assumed by exploring historical data or through expert opinion. Effectively, the calculation of these changes falls outside the scope of the model. Furthermore, each step is done by hand. This means that if one wants to change the forecasting period, new assumptions need to be made and a large amount of the process repeated. Much as in other models and frameworks, the process is linear rather than dynamic.

When it comes to computer-based food security simulation modellers have adopted a few broad approaches. Some studies have attacked the problem of food security through an economic approach with the use of Computable General Equilibrium (CGE) models. Others have employed discrete finite state models, while system dynamics has also been identified and used as a possible modelling approach to simulate food security complexities adequately.

CGEs have been used by both Van Dijk et al. (2012) and Timilsina et al. (2012) however, still in two distinctly different manners. Van Dijk et al. (2012) use their economic CGE model in combination with a spatially explicit land use model to capture change at the global, national, and landscape level. The CGE is a global macroeconomic model and this is applied to a local spatial land use model to determine global economic effects on land use within Vietnam, and more specifically, how much of this land is likely to be dedicated to the growing of rice. Yield data is then applied to the resultant expected acreage under rice to determine whether rice production will meet national rice consumption. Considering the nation's population and expected growth, per capita consumption is tracked as the indicator of food security.

Timilsina et al. (2012) use their CGE model to analyse the long-term impacts of large-scale biofuel expansion on land use change, food supply and prices, and the overall economies of various countries. Again, the model is augmented with an explicit land use module. This model aims to determine the effects of certain biofuel targets on global and regional food supply. The model runs a variety of target scenarios and determines the potential global implications and regional implications for areas such as Sub Saharan Africa. Both CGE models discussed have the advantage of incorporating global economic trends as drivers of food security in their simulations. However, the significance of this in Malawi, a relatively isolated economy especially with respect to food production and consumption, is low. This does not mean that a CGE model at a more local level would not be valuable to assessing food security in Malawi but rather that the scale of these two CGE approaches is less meaningful to the Malawian smallholder farmers in question. Furthermore, what CGE models fail to model with significant meaning are the decision-making processes of the smallholder farmer. In reality, farmers are faced with a number of land-use choices. There are often social factors that affect the decision-making process in addition to economic and biophysical constraints and influencers. The model's ability to run a variety of scenarios under dynamic simulation is well suited to the problem at hand; however, a modelling methodology that can incorporate both farmer decision-making processes and the impact of social dynamics on decision making at the local level is preferential for this study.

The CLUE (Conversion of Land Use and its Effects) model also simulates land use change as a result of biophysical drivers but is expanded to include a variety of human drivers as well. CLUE is a discrete finite state model which aims to integrate environmental modelling with a graphical information system (Veldkamp & Fresco, 1996). The ability to include human drivers into the model makes it suited for the Malawian case in the context of important social and political drivers that influence the food system. At present, CLUE maps only land use change as a result of the different drivers and there is no food security indicator as a direct output. CLUE would, therefore, require some changes in order to fit this studies purpose. All that is required, however, would be the inclusion of a crop model to convert the acreage and associated land use that CLUE outputs to yields and then to per capita consumption as the food security indicator. This would make CLUE a very effective tool for modelling food security in Malawi at both the national and regional scale.

CLUE is a spatial model, and this means that the smallest unit of analysis is a grid-cell and each of these cells is assumed to be internally uniform. Land use changes are only triggered when the biophysical and human demands can no longer be met. This means that there are three primary drawbacks for modelling smallholder household food security. The first is that if two grids have similar biophysical constraints (soil, rainfall, temperatures, relief etc.) and similar human drivers (population, technology level, level of affluence, politics, attitudes and values) then the land use outcome will almost certainly be the same. This allows for no room for the impact of decisions at the household level. Furthermore, it provides no distinction of the affluence between households because each grid-cell would need to be assigned an aggregate affluence indicator. For example, if the model returns sugarcane as the best use of the land and the land is split unevenly between farmers; economies of scale might mean that although suitable for farmers with larger land holdings, those with smaller land holdings might be subject to other feedbacks that make the CLUE output unviable. The second is that there is a large burden on the choice of the initial land use. Land use only changes when biophysical and human demands cannot be met and this means that a less than optimal land use solution might be outputted as long as it can meet the demands of the drivers. Thus, there is likely a quicker path to food security than this model would suggest and makes this model less than optimal itself for policy creation. This model can run checks on proposed policies, but is not fit for policy generation. Thirdly, CLUE does not consider land use modifications such as increased input use or increased land management levels. Factors of this nature are significant to smallholder farmers and must be included in the modelling process if an accurate household-level model is to be constructed.

System dynamics has also been proposed for food security modelling. Christos et al. (2014) propose system dynamics as an *approach that captures the dynamic nature of the interrelations of food security aspects in a sustainability context and that further allows the assessment of different policy interventions*. Christos et al. (2014) maintain that system dynamics can be used to create a quantitative strategic decision-making tool for use in both the public and private sectors. Muetzelfeldt (2010) provides an in-depth proposal outlining how system dynamics can be used to *represent influences and other relationships between the main agricultural and food system drivers and their consequences.* He concludes that an *approach based on system dynamics has the potential to represent complex system interactions in a formal, standardized way; and that such representations can also form the basis for computable qualitative or quantitative models*.

Stave and Kopainsky (2015) explored how system dynamics can be used to explain food supply vulnerability even as a purely conceptual model. They also reason that the mapping tools within the system dynamics methodology, which are used prior to quantitative and qualitative simulation, help structure thinking about where and how different disturbances might affect particular systems. Another potential benefit of the system dynamics process which Stave and Kopainsky (2015) raise, is that the visual representations and the process of creating them can serve different purposes for various stakeholders. Because of this, system dynamics aids the modeller in the transition from mental models to formal simulation models. Finally, after arguing for the solution to be of a mathematic sense Saeed (2003) proposes that system dynamics is best suited to the job, a job that entails building and experimenting with computer models of problematic patterns that are representative of developmental problems.

Both (Lambin *et al.*, 2000) and (Thompson & Scoones, 2009) state that urban and peri-urban land allocation models are more developed than that of rural land allocation models and that a deeper understanding of these 'rural worlds' and their potential pathways to sustainability through agriculture is needed.

2.5.3.1 How has system dynamics been used to model food security before?

There are a number of studies that use system dynamics to create full simulation models in order to provide meaningful mathematical results to help understand and treat food and food security-related issues. This study identified 5 such studies that include both completed system dynamics simulations and food security issues.

The first is a study titled **System Dynamics Model to Support Rice Production and Distribution for Food Security** by Suryani *et al.* (2014). This model uses system dynamics modelling to evaluate the effect of changes in regional conditions along with several different potential policy options on food security in Indonesia. This is a national level model and therefore only national aggregate data are used. There are a number of policies on the table that will shape land intensification, land expansion, and food distribution in Indonesia and the model is constructed to determine the effect of these drivers on food security. Rice production is monitored as the food security indicator. Notably, this is a pilot study and the authors suggest further research is required to incorporate the effects of national food logistics.

The second study is titled **Agricultural Land Use and Food Security in Asia: Green Revolution and Beyond** by Saeed (2000). The study explores the patterns of growth in agricultural production and land use for a variety of Asian countries. This model is a multinational level model. The model aims to map the relationships between the population, land usage, yields, land degradation, and investments. The model monitors food production per capita and GDP as food security indicators. The model determines that agricultural resources are being strained on a whole-scale level across the considered countries and could lead to a widespread decline in agricultural outputs threatening food security. National aggregate data are used in determining trends in national food production agricultural resource stocks, and per capita consumption.

The third study is titled **Food Provision and Environmental Goals in the Swiss Agri-Food System: System Dynamics and the Social-ecological Systems Framework** by Kopainsky, Huber and Pedercini (2015). This simulation models national food production, greenhouse gas emissions, food imports, and soil fertility. The model tracks a self-sufficiency ratio as the food security indicator combined with a monetary capital stock which tracks the ability of the nation to import the difference in national food production and domestic consumption. It is important to remember that this study aims to model the trade-off between food provision and environmental sustainability where food security is not the primary concern, but rather just one of them. This simulation models a socio-economic system (SES) and the case study concludes that system dynamics can make an important contribution in simulating systems that contain feedback loops and are nonlinear in nature. The model is constructed with national-level data to model total domestic food security and sustainability.

The fourth study identified is that of Georgiadis, Vlachos and Iakovou (2005) and is titled **A system dynamics modelling framework for the strategic supply chain management of food chains.** Georgiadis, Vlachos and Iakovou's model is more a study of how system dynamics can be applied to supply chain management than food security, but the selection of a food supply chain for the model application and case study requires that the study is reviewed for potential overlaps and parallels with the study at hand. Georgiadis, Vlachos and Iakovou (2005) found the use of system dynamics particularly useful in the modelling of variables that need to mimic those that in reality have high seasonality. Georgiadis, Vlachos and Iakovou found that the strength of the model is in its ability to conduct various "what-if" analyses. They suggest that the model can be tailored for use in a wide variety of food supply chains. One must remember that this model deals with supply chains, which is a post-production system and is different from the other models considered here that include food production within the system. However, this does prove that the system dynamics framework, methodology, and modelling procedure can be applied to multiple systems and is a versatile modelling framework.

The final completed system dynamics simulation under consideration is that of Stephen Conrad (2004) entitled **The Dynamics of Agricultural Commodities and their Responses to Disruptions of Considerable Magnitude**. The model is an agricultural production cycle which includes the corn, beef, and dairy sectors within the United States. The model explores the effects of large-scale disruptive events on the production cycles of these three food products. As a proof of concept exercise, a disruption scenario in which foot-and-mouth disease (FMD) is introduced to the United States was simulated and the effects on the industry were gauged under the present policy and two alternative policies which were identified to better manage the effects of a potential disruptor. Again, the model maps an entire countries production and consumption at the national level. Furthermore, the model only models three agricultural commodities. These commodities contribute to food security but this is not the same as modelling food security. For example, the collapse of the dairy sector might be cause for economic concern and pose a major inconvenience for many, but national food security

Table 2.1: *Cases of System Dynamics Models Related to Food Security*

Study No.	Author	Region	Level of Development	Strictly models food security	Scale	Food security indicator	In context of
1	(Suryani *et al.*, 2014)	Indonesia	Developing	Yes	National level	National rice production	Land expansion + intensification
2	(Saeed, 2000)	Asia	Both	Yes	Multi-national level	Per capita food production	Global economies
3	(Kopainsky *et al.*, 2015)	Switzerland	Developed	Yes	National Level	Self-sufficiency ratio	Environmental sustainability
4	(Georgiadis *et al.*, 2005)	Greece	Developed	No	National level	NA	Supply chain management
5	(Conrad, 2004)	United States	Developed	Partially	National level	Price of beef	Corn, beef, dairy industry economics

The brief review of these five system dynamics, food security, and food industry incorporated studies yields an interesting result. There is no completed simulation household-level food security system dynamics model that exists in the literature. This is most likely a result of the targeted end users of most models. Most models aim to generate results useful to policymakers who are charged with writing policy to ensure food security. National or regional level policy naturally requires policy based on national or regional level system understanding. Unfortunately, policy that is good for most is seldom good for all. Thus, policy that will best benefit a nation as a whole could still lead to the further marginalisation of those most food insecure. A simulation that models the household-level system would be most apt at generating results both useful and beneficial to the household.

2.6 Industrial crops and food security

The role of the industrial crop (IC) in our world's future is heavily contested. On one hand, it could prove critical in reducing our dependency on fossil fuels and could lead to a far greener future. On the other, there are major concerns that ICs will adversely affect food security, especially in the world’s developing nations. The concern is that ICs compete directly with food crops for the productive resources of land, water, and labour (amongst others) and will thus lead to a reduction in food production if the development of these crops is pursued. ICs extend far beyond just the biofuel realm, collectively known as fuel crops, and extend to include all crops that are grown for industrial or non-food purposes. Cash crops will also be included in the definition of an IC as although a select few of these crops might be classified as food, the intended end use is consumption, after processing, in a foreign market. Furthermore, many of these crops cannot significantly contribute to local diets, such as cocoa, even if they are readily obtainable locally (Wiggins, Henley et al. 2015).

Opponents of IC expansion argue that it creates unnecessary food security risk for third world farmers who must be self-sufficient in basic staples in the absence of food markets (Fafchamps 1992). Rural markets are said to be thin and isolated owing to low levels of infrastructure, associated high transport charges, and generally low agricultural output. Because of this, there is a correlation between food prices and a farmer’s own agricultural production. Furthermore, if there was access to open markets, opponents maintain that smallholder farmers would be exposed to market risks such as price volatility and become pawns in supply chains that are governed by large corporations (Wiggins, Henley et al. 2015). There are also concerns that ensuing monocropping would leave a region highly susceptible to the movements of a single industry or vulnerable to weather, pests etc. that might plague a particular crop leading to regional or even national crises. Allocating more land away from the production of food crops, especially staples, could see regional or global shortages of a particular crop. This would lead to major price spikes which would exacerbate the position of the poor (Dawe, Peter Timmer 2012). It also bodes trouble for a region or nation who aims to become self-sufficient and would lead to reliance on heavy food imports instead (Oosterveer, Adjei et al. 2014).

Land use change is a concept commonly associated with ICs. Opponents to IC expansion not only worry that food-producing land might be handed over to IC cultivation but that IC expansion would lead to the conversion of natural jungles, savannahs, or grasslands to farmland leading to environmental degradation. The role of these lands in food security will differ greatly depending on the type of land use change but in the African perspective, these lands almost always act as grazing land for cattle and other livestock. A reduction in grazing land would reduce the numbers of livestock that the region would be able to support. This would adversely affect food security as livestock is thought to be an important buffer between drought and human suffering.

IC expansion proponents argue that the farming of cash crops, fuel crops, and other industrial crops allow households to increase their incomes by producing that crop which yields the greatest returns for their investment of land and labour (Govereh, Jayne 2003). Greater income leads to greater food security especially with respect to food diversity and putting a variety of foods on the table. When IC expansion takes the form of large plantations there are a variety of other benefits. One major benefit is the creation of permanent jobs. Furthermore, the creation of white collar jobs, which are often not immediately filled by locals, leads to an influx of wealth which injects more money into the local economy. Another direct benefit is that the inflow of irrigation and fertiliser leads to spillover effects that increase both access and knowledge regarding these two inputs for the local farmer.

Proponents of IC development also assert that it allows for the smallholder farmer to access various support services, such as financial, technical and extension services (Onumah, Williams et al. 2014). The farmers of developing nations often encounter major hindrances to obtaining finance and this is thought to severely prevent farmers from accessing the inputs they need. In many regions, agricultural credit is principally available through interlocked cash crop schemes (Dorward et al., 1998) and thus farmers are more likely to have access to crucial inputs when there is IC development. Access to inputs such as seeds, insecticides, herbicides, machinery, fuel, transport and labour (Onumah, Williams et al. 2014) would greatly increase yields and efficiency thereby positively affecting food security.

There are also many indirect benefits. Especially in the case of larger plantations or collective agricultural endeavours, infrastructural development often follows in the form of paved roads, electricity, clinics, schools and even shops; all of which can indirectly increase food security (remember how road density is a food security indicator in the EIU's model). This also leads to spin-off industries as evidenced in Swaziland. Here, nurseries were created to provide sugar plantations with mango trees - used as fire breaks - and where a small fishing industry was born from the large irrigation canals.

This very debate, specifically where it is concerned with biofuel production from fuel crops is known as the food vs fuel debate. Those who argue against biofuel production argue that any volatility in the energy market would then be transferred to the food market leading to higher price peaks (Bindraban, Bulte et al. 2009). On the other hand, higher food prices owing to biofuels mean that farmers would receive more money for their agricultural products during times of surplus food crops (Negash, Swinnen 2013) when prices are generally low. To combat concerns, many proponents reason for the use of idle or marginal land for biofuel production (Kgathi, Mfundisi et al. 2012) which a case study shows might work for eastern Botswana where almost 70% of the land is idle. Another proposed solution is the use of second or third generation biofuels, those which are manufactured from non-food crops - such as wood or waste – and those based on biomass improvements – such as algae.

Another case study 'Micro-evidence from Ethiopia' (Negash, Swinnen 2013) shows that households participating in biofuel production – castor – saw food security increases. Here both food consumption increases and food gaps decreased by approximately 25% and that in this particular case food and fuel proved not competitive but complementary. In Mozambique, however, land has been given to large-scale plantations, land that was previously promised to displaced communities (Cotula, Dyer et al. 2008) after the creation of the Limpopo Transfrontier Park. Cotula, Dyer et al. (2008) draw attention to the fact that where suitable conditions are not in place poorer groups can lose access to the land on which they depend. For benefits to be realised land tenure security must be maintained and under the right conditions land use and livelihoods in rural areas can be revitalised.

The benefits or drawbacks of IC expansion are then certainly context specific. Its success is heavily dependent on both policy and programme structure of government and private initiatives. Therefore, governments need to take smallholder farmers and landowners into consideration and promote biofuel - and IC – policies that protect smallholder needs and interests (Amigun, Musango et al. 2011). The feedbacks within the system are of a complex nature and a deep understanding of the determinants at play is necessary if one is to forecast the potential impacts of IC expansion and land use change within a particular locality or even nation.

2.7 Malawi

The state of food security in Malawi is dire. Malawi is home to more than 16 million people of which 80 - 85% is classified as rural. The Bioenergy and Food Security Projects (BEFS) division of the FAO (Leete *et al.*, 2013) estimate that 52% of the country's population lives beneath the poverty line and that 27% are undernourished. As a result, in 2010 it was found that 45% of children under the age of 5 were stunted. Stunting is one of the major indicators of undernutrition and refers to a child having a low height-to-age ratio in comparison with healthy children of the same age. Consistent low-quality diets can lead to serious cognitive underdevelopment, below par school attainment, and low per capita income (Martorell, Horta, Adair, Stein, Richter, *et al.*, 2010). The effect, however, is felt much higher up the economic chain and the cumulative effects of household-level food insecurity are felt in regional and even national economies, which result in individuals and households bearing a double burden. According to the EIU's global food security index (EIU, 2015), Malawi achieves a score of 31.4 out of a possible 100 points and is ranked 105 out of the 113 index countries - slightly ahead of other African states such as Burkina Faso and the Democratic Republic of the Congo (DRC). Food security is high on the agenda for Malawi and rightly so, the effects of ICs in the country's future could lead to food security disasters or prove a vital aid in the nation's quest for achieving a more food secure future.

2.7.1 Agriculture in Malawi

In the context of food security and industrial crops, Malawi proves an ideal case study. The agricultural sector employs roughly 73% of the total labour force and agricultural outputs account for 89% of national export (Leete *et al.*, 2013). The farming sector is dominated by subsistence-based rain-fed agriculture and large-scale IC plantations, which represent the two major stakeholders in this study; that of IC expansionists and the smallholder community who might be affected – for good or bad - most. Malawi sits on massive water reserves and has access to over 17 billion cubic meters of renewable water resources; however, irrigation is low and only 5% of this is withdrawn annually; of which 84% is consumed in the agricultural sector.

Of Malawi's 11.8 million hectares (ha) around 59% is cultivatable and 40% is arable. Malawi's agricultural sector is divided into two major subsectors, that of smallholder subsistence farmers and that of large plantations - also called estates. The smallholder sector is comprised of an estimated 2 million families that occupy around 4.5 million hectares of land (FAO Commodities and Trade Division, 2003). The following table shows the size of smallholder farms and the number of farming families within each range:

Table 2.2: *Smallholder Plot Size Distribution*

Smallholding size (ha)	Families (%)
< 0.5	25
0.5 – 1	30
1 – 2	31
> 2	14

Malawi's smallholder farmers have very low access to inputs and thus farming is categorised as low-input low-output farming. Despite this, Malawi's informal farming sector produces 80% of the food used for domestic consumption and 20% of the country's agricultural exports. Cassava, potatoes and maize, in particular, dominate smallholder sector production. Although food production, in terms of volume, is very similar between cassava, potatoes and maize; maize accounts for more than 50% of daily caloric consumption within Malawi and covers more acreage than any other crop (FAO Commodities and Trade Division, 2003). Potatoes account for 8.4%, cassava for 5.8% and livestock and animal products account for only 3.8% of daily caloric intake.

2.7.1.1 Maize

Maize, which originates in Latin America, is thought to have found its way to East Africa in the 16th century (Jaicaf, 2008). It has all but entirely replaced the indigenous and traditional subsistence crops of sorghum and millet which now account for less than 10% of the total area planted. Maize accounts for more than 60% of the total area planted and is the staple food of choice throughout Malawi. Of households that are involved in cultivation, 97 % of them grew maize (NSO, 2005).

Malawi is highly dependent on maize, in fact, only Zambia is more dependent on maize as a calorie source, and maize accounts for roughly 54% of household caloric intake (Minot, 2010). White maize is milled and then mixed with boiling water to create the local staple dish called nsima.

This dependence on maize, coupled with the fact that most smallholder agriculture in Malawi is rain-fed, leads to high instability in staple food prices. Maize cultivation without the application of fertilizers leads to the quick degradation of the soil. The lack of widespread correct or sufficient fertilizer application in Malawi is an unsustainable farming practice and further contributes to maize yield instability (Jaicaf, 2008).

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Most of the traditional maize varieties grown in Malawi are flint-type; however, the recent introduction of new varieties has led to crossbreds of the traditional varieties with dent varieties to form composite varieties. Composite varieties are also formed by crossbreeding traditional varieties with commercially available synthetic and hybrid varieties (Jaicaf, 2008). The majority of land under maize is still planted with the traditional varieties, especially in rural areas. However, composite and hybrid varieties are more prevalent in cities and surrounds.

The traditional varieties are considered late maturing and are generally planted at the beginning of the rainy season (November/December) and grown through to the end of the rainy season (April). Despite a lack of vitamin A contributing to nutritional deficiencies in many Malawians, white maize is preferred over yellow maize owing to the mentality that yellow maize is animal feed (Jaicaf, 2008). However, in truth, the yellowing of certain maize is the result of a particular pigment which is converted into Vitamin A during digestion (Muzhingi, Gadaga, Siwela, Grusak, Russell, *et al.*, 2011) and the adoption of yellow maize as a food source would greatly aid in combatting vitamin A deficiencies in many Malawians.

The maize yields achieved in Malawi fluctuate greatly based on climatic conditions but are considered low. The combination of low yields and high variability leads to the occurrence of a famine every 2-3 years (Jaicaf, 2008). Malawi achieves average yields between 1 - 1.8 t/ha, however, this is far below the world average of 4.2 t/ha.

Maize is grown on permanently cultivated land. This land is prepared at the end of the dry season through a process of 'slash and burn.' The fields are cleared of major obstacles (however mango trees are often left standing) and the fields are burnt. The ash produced through burning is then used as a means of fertilization in order to help prevent the degradation of the land as a result of continual cultivation on these fields, however, there is little proof that this process attests significant benefits (Jaicaf, 2008). Nonetheless, the burning of fields also aids in the clearing process by removing obstacles to ploughing and further helps in destroying organic matter which leads to better termite control. Ploughing is done in the form of hilling, and in Malawi, this is done by hand using a hoe. Hilling is also mostly done by women and the furrow is normally kept 80-100 cm wide. Malawians traditionally sow 10-20 kg of maize seed per hectare with inter-row and inter-stock spaces averaging around 90cm each. Traditional varieties receive no top dressing or chemical fertilizer in most cases, however, after the maize has germinated, haricots, soya, chickpeas, and black-eyed peas are planted to provide the maize with nitrogen (Jaicaf, 2008). This is known as intercropping. After the end of the rainy season, the maize is left to dry in the field and then harvested by hand.

Maize is primarily used for food; however, it is also used as animal feed or is brewed to make alcohol. Two variations of the staple dish nsima exist and are classified according to the milling method used. Mgaiwa is more nutritious, however, is often considered inferior in colour, and ufa has lower nutritional value but is prized in terms of its colour. Maize is usually dry milled but wet milling also occurs and is a method that has been introduced from Europe relatively recently. There are also soft drinks in Malawi that are made from maize.

Maize prices are governed largely by the domestic market and trends in supply and demand (Minot, 2010). This is a result of Malawi's very low maize imports and exports relative to annual production. In times of drought, Malawi has imported maize from neighbours Mozambique and often from South Africa but large distances, cross-border fees, and poor infrastructure lead to high import prices. In fact, maize imports are estimated to cost almost five times as much as locally grown maize; a price at which most Malawians cannot afford unless subsidized by the government such as during severe maize shortages during 2002-03 (Levy, 2003). This shows that importing food as a means to ensure food security is a costly and unsustainable approach. This is exacerbated by the fact that Malawi is a landlocked country and therefore has no seaport. During times of surplus, Malawi has exported maize to crises stricken Zimbabwe and even to Kenya. However, international trade with other southern African countries is often hampered by the fact that times of famine and surplus often coincide.

Because of the country's considerable dependence on maize and the fact that almost all maize is harvested between April and July, with the exception of green maize harvested in late February or March, the months of greatest food insecurity are December and January.

2.7.1.2 Cassava

Cassava or manioc, like maize, came to Africa through Portuguese traders from South America. Alongside maize, cassava helped transform the agricultural sector in Malawi away from the traditional crops of sorghum and millet (Haggblade & Hazell, 2010). Under British rule, the colonial authorities not only encouraged but sometimes obliged farmers to plant cassava as a preventative measure against possible drought and famine. Therefore, it is evident that even in the first half of the 20th-century cassava was considered an important measure to ensure food security. After gaining independence from Britain, early government policies largely encouraged maize production over that of cassava; however, in the 1980s and 1990s cassava saw an incredible resurgence in popularity owing to a number of natural and social events that advocated for increased production of the tuber.

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In 1986 Malawi's cassava crops were ravaged by the cassava mealybug (CM) and the cassava green mite (CGM), introduced either from Zambia or Tanzania (Haggblade & Hazell, 2010). At a similar time, drought endangered Malawi's maize crop and the country was left increasingly vulnerable to food shortages. By January 1988 Malawi had declared a national food emergency and the country was forced into action. The response took two forms, first that of biological control and second that of an invested research effort into selecting and improving cassava varieties.

Efforts to control the mealybug through biological means centred on the mass rearing of the E. Lopezi wasp, a natural predator of the mealybug (Haggblade & Zulu, 2003). Malawi, alongside Zambia, with the help of overseas aid, then embarked on research efforts to mitigate the crises. The focus was initially on identifying the most resistant local varieties, varieties resistant not only to CM and CGM, but varieties also resistant to the cassava mosaic virus (CMV). Then 2 years later, improved versions of these local varieties were released just at the same time that the government started to roll back large-scale maize subsidies.

Pre-1994 and its "Accelerated Multiplication and Distribution of Cassava and Sweet Potato Planting Materials as a Drought Recovery Measure in Malawi" program initiated by the Government of Malawi (GOM), cassava yields were low and traditional varieties yields averaged at around 6 tons per hectare. The newly developed varieties, however, managed to yield 20 – 30 tons per hectare. This vastly improved yield coupled with the end of aggressive government maize subsidies led to a massive resurgence in cassava production as more land was dedicated to cassava planting (Haggblade & Zulu, 2003). In reality, smallholder farmers only achieved about 14 tons per hectare but this was still around double the yields of earlier varieties during a good year.

Cassava is a tuber and can be classified into two general types; bitter and sweet. Cassava's value as crop, while many Malawian prefer maize as their staple dish, comes from its resilience to various climatic conditions. It grows best when rainfall is abundant but can still grow in areas where rainfall is as low as 500 mm provided that it is well distributed. It can also grow in areas where rainfall is over 5000 mm. Perhaps most important, however, is the fact that the crop can survive periods of prolonged drought where almost all other food crops might die. During this time the plant enters a dormancy period and will resume growth when rainfall resumes. Dormancy can last 2 to 3 months and the plant often sheds leaves in order to limit transpiration when moisture availability is low only to regrow them when rains return (Directorate Plant Production, 2010).

Cassava can be grown in virgin forest land or on land previously cultivated with other crops. The land must be cleared through slashing and burning so that the crop does not have to compete with other plants. Burning aids in destroying parasites and the ash is used to increase the quantity of potassium salts (Directorate Plant Production, 2010). Hilling is done by hoe and spacing between rows is 80 – 100 cm, however, this varies according to local weather patterns. Areas of more fertile soil contain up to 15 000 plants per hectare and areas of land considered more marginal contain around 10 000 plants per hectare. Cassava is propagated not through seeds but by the planting of cuttings yielding properties almost identical to the parent plant (Haggblade & Zulu, 2003). This coupled with the fact that Malawian farmers use virtually no purchased inputs in cassava farming, means that farmers need little capital or credit access to get underway (Haggblade & Hazell, 2010). Instead, to obtain cuttings, many Malawians trade labour – a practice referred to locally as Ganyu – and in return receive payment in the form of cuttings from another farmer's cassava plot. Despite smallholder farmers using limited to no purchased inputs on their cassava crops, cassava does respond well to fertiliser use and requires some application of N and K fertilizers to achieve maximum root yields (Olasantan, Lucas & Ezumah, 1994).

Cassava has a long and varied cropping cycle and this allows for increased flexibility with regards to crop planting and harvesting times. This flexible cropping calendar proves a significant advantage for smallholder farmers who often experience major labour constraints during peak land preparation, planting, and harvesting times. Traditional varieties of cassava were sometimes harvested as late as 30 months after planting, however, improved varieties released in the 1990s bulked 12 months earlier with much greater yield (Haggblade & Hazell, 2010). The cassava planted today can be harvested anywhere between 6 months and 3 years after planting (Directorate Plant Production, 2010), however, it is most common to plant cassava at the beginning of the rainy season (November/December) and harvest during the end of the dry season (October/November) allowing enough time for land preparation to ensure planting before the next rains. This equates to an 11-12 month crop cycle. Cassava does not keep well in its fresh state and will last a maximum of a few days after harvest before going bad (Coursey, 1973); however, cassava can be left in the ground for up to 36 months and will continue to grow until around 18 – 20 months, after which growth will stop but the starch content will continue to rise (Directorate Plant Production, 2010). Cassava is also often harvested after 18 months and allowed to grow through a second rainy season owing to its abilities to go into dormancy to survive the dry season. This also serves as an important food security measure for many Malawian families as it can be harvested if necessary during the hunger months of December and January. Cassava is harvested by hand after the stalks are topped. Cuttings are set aside for the next planting and the remainder is burned. The remaining stalk is used as a handle to pull the tubers from the ground.

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It is important to note that uncooked cassava is toxic and largely unfit for human consumption owing to the presence of cyanogenic glycoside linamarin and lotaustralin (Coursey, 1973). These substances hydrolyse to form hydrogen cyanide (HCN). The toxicity differs largely between the two cultivars of sweet and bitter cassava. Sweet varieties tend to have lower toxicity than bitter varieties, however, the correlation is not exact and variation in toxicity is also dependent on ecological conditions during the plant's growth period. Cyanide content can be decreased dramatically by causing liberation of the HCN through volatilization or solution in water (Coursey, 1973). This takes the form of soaking, roasting, boiling or fermenting the cassava roots. Although there exist cases of chronic degenerative conditions and even death that are linked to the habitual large intake of cassava, this type of intoxication is relatively rare. Millions of humans and livestock consume cassava every day apparently without ailment and this suggests that traditional detoxification and cooking processes are, typically, exceptionally effective (Coursey, 1973).

In the cassava belt, it is grown almost singularly for home consumption as less than 10% of production is marketed (Minot, 2010). In this manner, the bitter variety is most popular, and after soaking and fermentation, is dried and milled into a flour called kondowole. Here cassava is eaten throughout the year as a staple. Near the cities, cassava is grown commercially for consumption from November to April when maize is less readily available and takes the form of dried cassava chips called makaka. The FAO reports that Malawi has almost no formal cassava trade with any neighbouring countries, however, Kambewaa and Nyembe (2008) report that there is significant informal trade with Mozambique which acts as a source of cassava for both Zomba and Blantyre. This would also explain why cassava prices are higher in the Southern Malawi areas of Zomba and Blantyre. Prices in the southern cities can be up to four times greater than in the north. This high spatial variation in price, as one moves away from the higher production areas of the north, is likely a result of the high cost of transporting a commodity with a low value-bulk ratio and also a result of cassava being highly perishable after harvest (Kambewa & Nyembe, 2008).

There is also a distinct correlation between cassava prices and the season. Interestingly, it has an inverse relationship with the maize price. When maize supply is low, cassava is readily available as it is favoured over the high cost of maize during this time. When maize supply is high and the cost low, most cassava is being grown in preparation for a lack of maize during the beginning of the rainy season and is, therefore, harder to find. The prices during April to November range from 30 – 90% higher than from November to March (Minot, 2010). The fact that cassava is an important Malawian staple, and is seemingly an important crop in ensuring food security in a country where maize is king, makes it an important crop for investigation in this paper.

2.7.1.3 Potatoes

Like cassava, it is thought that potatoes originated in South America, either in the Andes of northern Bolivia or in southern Peru (Hawkes, 1990). Potato was then introduced to Europe and then spread to coastal areas in Africa by the Spanish or through Portuguese traders. It is also possible that it spread directly from tropical America Africa (Allemann, Laurie, Thiart & Vorster, 2004) probably on trade ships, or slaves ships returning to the African coast.

Both potato and sweet potato are important crops in Malawi. Although maize accounts for over half of the populations annual caloric intake, the FAO report that potatoes make up the second biggest source of calories for Malawians at 8.4 percent, followed closely by cassava at 5.8 percent (Leete *et al.*, 2013). In this estimate, it is likely that the FAO is including both Irish (white) potatoes and sweet potato in the same category. However, the large majority of this figure is made up of sweet potato as according to Malawi's National Statistical Office (NSO) and the International Food Policy Research Institute (IFPRI), in a joint report (Benson, Kaphuka, Kanyanda & Chinula, 2002) sweet potato accounts for 5.1% of Malawi's cropped area. With white potatoes being accounted for in the 2.1% attributed to other crops. However, these statistics range from census from the year 1995 through to 2000 after which Malawi saw potato yields rise by 50% in the mid-2000s and today they are almost double. Owing to increased yields, and resistance to droughts that decimated maize crops, Malawian smallholders have also dramatically increased their land allocation to potatoes. In 1990 the FAO reports that less than 35000 ha were planted and by 2013 this had grown to more than 250 000 ha (FAOSTAT, 2015). Production is reported to have increased from around 400 thousand tons to more than 4.5 million tons in 2013. Because sweet potato is significantly more popular than white potato in Malawi and because sweet potato has been identified as having an important role in Sub-Saharan food security this review will focus on the literature pertinent to sweet potato.

Crop diversity has been high on the agenda for Malawian policymakers. There are a number of physical and socioeconomic factors have contributed to the need for Malawi to diversify away from maize. Drought has been a major driver of change in this regard; maize is much more affected by extended dry spells than root and tuber crops such as potato and cassava. In the past policymakers encouraged growing maize even in marginal areas, however, in these areas the crop's success requires expensive fertilizer and other inputs. This was made possible through government fertilizer subsidies. The end of government subsidies coupled with the devaluation of the Malawi kwacha has led to a steep rise in the cost of farm inputs, which are vital to maize production (Minde, Teri, Saka, Rockman & Benesi, 1997). Without crop diversity, during times of drought and famine, Malawi has been forced to import maize from South Africa, however, this comes at a great cost and could well be averted through efforts to reduce the total dependence on maize (Scott, Labarta & Suarez, 2013).

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White and sweet potato, like cassava, are especially important as an effective measure against food insecurity in Malawi owing to its considerable tolerance to drought conditions and ability to achieve good yields even in marginal lands (Kathabwalika, Chilembwe, Mwale, Kambewa & Njoloma, 2013). Potatoes have other food security benefits as well. Potatoes are a source of vitamin C and important micronutrients. Sweet potato leaves can be eaten as a vegetable which contains chlorogenic acids, which helps prevent obesity in humans. The leaves also contain considerably higher amounts of minerals such as Zn, Cu, P, K, Fe and N than most commonly cultivated vegetables as well as being a good source of protein and fibre (Sun, Mu, Xi, Zhang & Chen, 2014). Sweet potato leaves are also more tolerant to diseases, pests, and high moisture content than other green leafy vegetables.

In recent years, Malawian smallholder farmers have consistently achieved yields between 16 and 17 tons per hectare (FAOSTAT, 2015). However, yields of up to 40 tons per hectare are possible with some varieties, and with sufficient irrigation and inputs. Sweet potato is a vine and is therefore planted from vine cuttings. First-time planters obtain the cuttings from relatives or neighbours often in exchange for labour – Ganyu. Despite efforts to teach sweet potato seed multiplication most Malawian smallholder farmers rely on sprouts for planting, however, this slows down planting as vine shortages continue to be a constraint (Moyo, Benesi, Chipungu, Mwale, Sandifoli, *et al.*, 2004).

Sweet potato grows well in warm climates and requires annual rainfall between 750-1000mm per year of which at least 500mm falling within the growing season. It can be grown from sea level to 1700m above sea level, making it ideal for growing in Malawi (Abidin, Carey, Mallubhotla & Sones, 2017). Farming sweet potato requires land clearing, land preparation, planting, weeding, and harvesting. There are several methods to grow sweet potato and it can be grown on ridges, mounds or flatbeds. Sweet potato does not grow well in waterlogged soil and this makes the use of mounds and ridges to ensure good drainage and soil aeration preferable over flatbeds. Mounds and ridges do however require more labour during land preparation. Mounds should be around 30cm in height and diameter with between 60 cm and 1-metre spaces in between. This gives 10 000 mounds per hectare.

The principle form of sweet potato production is the pure stand system. In one study, the International Potato Centre (CIP) (Sindi, Kiria, Low, Sopo & Abidin, 2013) found that almost 90% of smallholder farmers practised the pure stand method while less than 10% of household intercropped sweet potato with other crops. When intercropped, most farmers intercropped sweet potatoes with maize or beans. Interestingly, Abidin et al. (2017) report that from experience in Malawi that intercropping two rows of sweet potato with one row of maize lead to highest productivity, however, as seen above, this is seldom practised in some study areas.

The same study also found that the majority of farmers did not use any fertilizer in root production or in vine production. Furthermore, only 2.3% of respondents reported using both manure and organic fertilizer. However, sweet potatoes do respond well to fertilizer and although sweet potato grows well in marginal soils, yields can be dramatically improved through correct fertilizer application. Sweet potato, as a root crop, removes more potassium (K) and less nitrogen (N) and phosphorus (P) than cereals such as maize (Abidin *et al.*, 2017). All soils are different and thus can require vastly different fertilizer application; however, basic guidelines suggest applying 400kg of NPK 15:15:15 per hectare during planting and the application of 400kg of muriate of potash (MOP) six weeks into planting to ensure adequate K for the crop (Abidin *et al.*, 2017). On many African soils the application of K leads to good yield response. A study on potato production practices in northern Malawi found that even though many farmers were fertilizing with both manure and chemical fertilizers that yields remained low. Upon investigation, it was found that the fertilizers in use did not contain K, possibly explaining the low yields (Kateta, Kabambe & Lowole, 2015).

Sweet potato, although considered a hardy crop, is not immune to pests and diseases. Malawian sweet potato crops suffer from sweet potato virus disease (SPVD) which in some cases leads to crop losses as high as 98% (Kathabwalika *et al.*, 2013). The sweet potato weevil (Cylas formicarius) is a pest that can also lead to significant loss in quality or yield. White potatoes can also suffer from late blight and bacterial wilt. Therefore, training is required to ensure good cropping practices in order to combat pests and disease effectively. Potato and sweet potato production and management training in Malawi are limited. Sindi et al. (2013) found that only 14.5% of smallholder sweet potato farmer respondents had received any training, and more than half of the respondents could not identify a sweet potato infected with SPVD.

Malawi does not import or export any sweet potato through formal channels. A bioenergy and food security projects' (BEFS) brief reported that in 2009 Malawi only imported 452 tons and exported 428 tons of potatoes while the yearly production was almost 3.5 million tons. This equates to very nearly zero percent. Sweet potato prices vary according to season and location. Sweet potato grown further away from city markets is cheaper in order to cover transport costs to areas of higher demand (Moyo *et al.*, 2004). Sweet potato is also cheaper during the harvest periods and costs roughly double during the slack periods. At the national level, domestic potato prices are less vulnerable to external shocks. This is a result of the lack of significant trade of potatoes on the international market, and that most trade in potatoes is largely confined between industrialized nations; this is in stark contrast to cereals (Scott *et al.*, 2013). Furthermore, like cassava, in many regions in Malawi potatoes are used for home consumption.

2.7.2 Industrial crops

On the other hand, Malawi's estates are the major source of foreign revenue and account for 80% of agricultural export. The chief exports are tobacco, sugar, and tea; however, small quantities of cotton, coffee, and pulses are also exported. Tobacco is by far the largest export; accounting for almost 62% of total export by tonnage. The next largest exports are tea at 8.7%, sugar at 6.9% and coffee at 1.8% (FAOSTAT 2015).

2.7.2.1 Tobacco

Modern commercial tobacco can be traced back to a plant that was dispersed throughout both North and South America by Amerindians. They carried both Nicotiana rustica and Nicotiana tabacum as they travelled throughout the Americas and it is the latter that modern-day commercial tobacco has descended from. Until the very end of the 15th century no one outside of North and South America had any knowledge of the plant, however, today it is grown in over 120 countries worldwide (Goodman, 2005).

Tobacco production in Malawi can be traced back to the 1920s but the rapid expansion of leaf cultivation did not arise until the late 1970s when production increased almost 90% from that of the 1960s (Barratt, 2003). By the end of the 1970s production had increased to around 50 000 tons annually but today has risen to 200 000 tons. In 2011 Malawi reached its highest all-leaf production of 237 171 tons of tobacco but in the following year, the country did not even muster 80 000 tons (Tobacco Control Commission, 2016). This is a stern reminder that Malawi is heavily dependent on rain for its income and when the rains fail, so to do crops and livelihoods.

The year 1995 saw the ban that prevented smallholder farmers from growing burley tobacco lifted. Since then, there have been two avenues for the production of tobacco. The first is through the large-scale estates, which until the beginning of the 1990/1991 growing season had a complete monopoly over production. The second is through smallholder farmers, whereby a farmer can choose to grow burley tobacco on all or a portion of his land. This allows for two distinct but interlinked IC systems to form.

Within the smallholder tobacco growing sector, there are two systems by which smallholder farmers can engage with growing tobacco. The first, and the traditional system is that of the independent tobacco farmer. Here, the farmer registers with the Tobacco Control Commission (TCC) to obtain a production quota. After the tobacco is grown, it is sold on the auction floor. Here, the tobacco undergoes quality checks, leaf grading, and is weighed. The farmer will receive his money once the sale is made to one of the leaf buying companies, which is mediated by a company called Auction

Holdings Limited which runs the auction floors in Malawi. The major leaf buying companies in Malawi are Limbe Leaf, Alliance One, Japan Tobacco International (JTI), Malawi Leaf, and Premium Tama Tobacco Limited. In this way, independent growers are left to source their own capital or credit for the purchase of seed, inputs, and farming equipment. However, farmers still have access to some extension services through the Agricultural Research and Extension Trust (ARET) which is funded by a levy deducted off the proceeds of tobacco sales and is effectively owned entirely by tobacco farmers.

The second system is that of the Integrated Production System (IPS). This was introduced in 2011 and takes the form of a contractual agreement between the farmer and the leaf company. The leaf company agrees to buy a predetermined amount of tobacco from the farmer and the farmer agrees to sell his tobacco exclusively to the leaf company in question (Drope *et al.*, 2016). This system is supposed to ensure that overproduction of the leaf is mitigated and allows for some control over the quality of the leaf from the tobacco company. In this contract, farmers also receive the necessary inputs in the form of a loan from the leaf company.

The loan package is a source of some controversy. While access to credit and associated inputs is a lifeline for some, it has drawbacks. There are two primary concerns. The first is that these inputs are provided at a cost that is significantly higher than the cost of equivalent inputs on the open market. Secondly, the loan packages provided by the various leaf companies are extremely rigid. For example, one loan package provided by the Limbe Leaf Tobacco Company requires that in addition to receiving inputs pertaining to the growth of tobacco, farmers were also required to receive 12 kg of maize seed and 3 x 50 kg bags of fertilizer required for the growing of the maize. Furthermore, the loan package also included tree seedlings in order to ensure that trees are planted to help prevent the deforestation that is taken place as a result of leaf cultivation.

The rationale behind adding the maize seed and fertilizer is to ensure food security, which seems fair, but the reality is that a farmer who might choose not to grow maize in a particular year is trapped trying to repay a loan for items that he does not need let alone want. Adding to the controversy is the fact that all the prices of seed, inputs, and other items are listed in American dollars, a unit display that is not fair on Malawian smallholder farmers who have protested that it is difficult for them to understand (Drope *et al.*, 2016). Low levels of education mean that it is difficult for farmers to make informed decisions regarding the cost-effectiveness of loans because of a lack of understanding of interest on loans and currency conversions.

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Tobacco originates from a tropical climate, however, has been grown successfully in subtropical and temperate climates as well. The plant prefers relatively high humidity, average temperatures between 20 and 30 degrees Celsius, and rainfall between 500 and 1250 mm per annum that is well distributed (Department of Agriculture Forestry and Fisheries, 2016). Tobacco is to some extent resistant to drought, however, is sensitive to wet soils, and should not be grown in fields that pond or flood in heavy rains.

After clearing the land through the slash and burn technique, a farmer should ensure that the field is well drained and tilled before planting is undertaken. The ideal planting time for farmers who do not have access to irrigation is from the beginning of the rainy season; this is generally November but can be as early as October or as late as December. This is the ideal time for transplanting tobacco plants into the field but seedbed and nursery preparation should begin in June. The plants should have a plant spacing of roughly 60 cm and a row spacing of 90 - 100 cm. Tobacco is most affected in terms of yield and quality by nitrogen application and both under and over fertilization with nitrogen can have a negative effect. Typical loan packages supply Malawian tobacco farmers with 7 x 50 kg bags of NPK (15:18:18) fertilizer and a further 2 x 50 kg bags of urea (Drope *et al.*, 2016). This is considered adequate for both the nursery stage and field growing stage of tobacco growing. Weeding is important throughout but is especially crucial during the early stages of plant development.

The tobacco plant ripens from the ground upwards, and thus during harvesting, the entire plant is not harvested at the same time, but rather the leaves are cropped starting with the bottom leaves, which are often referred to as sand lugs. Once the leaves are harvested, the curing process can begin. Tobacco can be air, fire, flue, or sun cured. In Malawi, over 90 % of tobacco is burley tobacco which is air cured. Flue-cured tobacco is grown almost exclusively by the estates owing to a more complex curing process, while northern division dark fire-cured (NDDF) and southern division fire-cured (SDDF) are also grown but have become almost negligible in recent years (Gourichon & Chigowo, 2014). Burley or air-cured tobacco is hung up in barns or open-air shelters to dry for 6 – 8 weeks. In Malawi, these shelters are made with branches from local trees and the creation of new shelters for tobacco curing each year has contributed greatly to widespread deforestation in Malawi. Both the harvesting and curing processes mean that tobacco cultivation is a labour-intensive operation. It is argued that tobacco cultivation, because of its high labour requirements, will be able to better address issues of poverty and food insecurity because it will create more jobs than would be realised in the cultivation of other crops.

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Tobacco yields in Malawi are weather dependent and are thus poor when the rains are late or during drought but are otherwise consistent. Tobacco has not seen massive improvements in yields in recent years such as what was seen with potatoes and cassava after the introduction of new drought and virus resistant varieties. Drastic increases in yields in Malawi occurred much earlier than other crops and were last seen in the 1960s and 70s (Barratt, 2003). This is because the tobacco industry in Malawi is much more established as a result of vested western interest in tobacco production by means of multinational corporations and because its position as the largest foreign revenue income generator has ensured heavy government support and favourable policies. Average tobacco yields, therefore, sit as they have since the 1980s at between 700 and 1100 kg per hectare.

Tobacco prices in Malawi fell during the 1990s. This is likely the result of two major factors. The first is that the growth in production has largely exceeded the growth in demand in terms of exports which resulted in lower export prices. The second is that new growers have joined the ranks of Malawi's green gold growers and have flooded the market with a lower quality leaf as a result of their inexperience and possibly lack of inputs (Barratt, 2003). Tobacco prices in Malawi then saw a resurgence from 2007 – 2015 with the exception of low prices in 2011 (Dias, 2013). Generally speaking, tobacco prices are volatile and are governed by both global demand and local production.

Tobacco is by far Malawi's biggest export and accounts for over 60% of total exports by revenue (FAO Commodities and Trade Division, 2003). Its future, however, is uncertain at a time where the health risks of smoking tobacco are becoming better understood and the practice increasingly frowned upon. Global policies and regulations have begun to take a progressive stance against the wholesale of tobacco in various forms such as prohibiting advertising and imposing high taxation on tobacco products. Globally, this has led to tobacco prices plummeting in recent years (FAO: Trade and Markets Division 2003). This will prove dangerous to Malawi's export sector as Malawi is heavily invested in the growing of burley tobacco. Malawi's tobacco industry fell by 2% in terms of contribution to total GDP from 18% in the year 1999 to 16% in 2009 (Leete, Damen et al. 2013). Malawi's small industry is evidence of the fact that most agricultural products are exported raw. In the face of a declining tobacco industry, this could prove to be a good thing, as cropland could easily be diverted to the growing of other, more sustainable crops without seeing the entire economy collapse owing to dependence on a massive tobacco processing industry. However, currently, the unit value of tobacco is still vastly higher than that of tea, coffee or sugar and proves a crucial avenue for many Malawians to attain US dollars in hard currency. In fact, despite industry uncertainty regarding tobacco growing, the leaf can still be so lucrative that it is popularly referred to as green gold (Orr, 2000). It is because of this that tobacco cultivation might still play a significant role in poverty alleviation and increasing food security in Malawi.

2.7.2.2 Sugarcane

Some species of sugarcane originated in northeast India while other species of sugarcane originated in Southeast Asia (Purseglove, 1972). Sugarcane is a tall perennial true grass and the first recorded production of crystalline sugar was in northern India. The grass was spread by Arab traders to Mesopotamia, North Africa, and the Mediterranean and was one of the first crops brought to the Americas by the Spanish and Portuguese and eventually to Africa by the Portuguese (Purseglove, 1972).

Sugarcane cultivation in Malawi began when the Lonrho Sugar Corporation (LSC) initiated its first sugar project in 1965 at Nchalo (Gosnell, 2005). The project culminated in the opening of the first sugar estate in Malawi in 1968 and the creation of the Sugar Corporation of Malawi (SUCOMA). Ten years later another sugar project was initiated in Dwangwa by the Dwangwa Sugar Corporation (DWASCO) in which the government was the majority shareholder. At the same time, a government parastatal was set up called the Smallholder Sugar Authority (SSA). The SSA leased a 500-hectare plot from Lonrho in which it established a settlement scheme on which 200 farmers would work (Chinsinga, 2016). After this, in both the sugar growing areas of Nchalo and Dwangwa the land handed over for sugar production was steadily increased. This was land that had previously been customary land but has been legally transferred and sanctioned through a series of presidential orders. This has caused controversy owing to the already low land per capita ratios and that many Malawians depend heavily on these small plots of land for their survival. For example, the Dwnagwa cane growing allotment in 1975 was 8750 hectares of prime, once customary, lakeshore land. By 2011 this had increased to 13 102 hectares.

Although the sugar industry seemed a key pathway into industrialization for Malawi it quickly became a tool for political patronage in which government elites used their influence within the sugar sector to garner support during Malawi's one-party era and in the fledgeling democracy that emerged in the years immediately after (Chinsinga, 2016). Party loyalists were rewarded with sugar distribution quotas. In 1998 the sugar industry was privatised. Both SUCOMA and DWASCO were taken over by the South African Illovo Sugar Group and since then Illovo has effectively had control over Malawi's entire milling and refining capacity as it owns both the mill at Nchalo and Dwangwa. However, reports of the construction of a government-owned mill in Salima have emerged (Maingo, 2016) despite very limited cane growth in the area and uncertainty over market readiness for a new mill.

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The Green Belt Initiative (GBI) was initiated as a measure to improve food security in 2010 by irrigating a million hectares of land within a 20km zone of the countries enormous water reserves. Despite being framed as a response to food security issues the initiative barely involves the country's staple food crops of maize, sweet potato, cassava, and rice (Chinsinga, 2016). Instead, it is sugarcane that features. The government's recent infatuation with sugarcane is because of the country's over-dependence on tobacco, a crop under serious threat. Tobacco is Malawi's chief foreign exchange earner and constitutes a significant portion its GDP (Chinsinga, 2016). Sugar is seen as a potential alternative to tobacco and has already outpaced tea to become Malawi's second largest export in value.

As a whole, the Malawi sugar industry is efficient. Production is high and average sucrose levels of 14.3% are unrivalled by any other country in the Southern African arena (Chinsinga, 2016). Sugar is produced at a cost of just 7 US cents per pound and this means the industry competes globally despite Malawi being a landlocked country with poor infrastructure. Adding to the sugar industry's security is that Malawi prohibits the import of sugar which ensures domestic demand and helps protect the industry from global sugar demand and price fluctuations. Success also stems from the EU's continued support of the industry which offers support for smallholder outgrower schemes in particular. The government argues that expanding sugarcane cultivation helps reduce poverty and contributes towards food security by providing an avenue for increased income through cane sales to the mills.

Traditional Authorities (TAs) are critical to the government's strategy in order to mediate the government's access to the land that is necessary for sugar expansion that, although designated as part of the almost 50 000 hectares of land set aside by the late president Kamuzu Banda in 1969, is now being utilized by smallholder farmer communities (Chinsinga, 2016). These TAs have the power to reassign or designate land at their prerogative, however, with land at a premium, there is no clear proposal as for where this land might hail from.

Sugarcane requires a warm tropical or subtropical climate and rainfall between 1100 and 1500mm is considered adequate provided good distribution (Department of Agriculture, Forestry and Fisheries 2014). The plant favours high humidity and extended sunlight days of 12 – 14 hours. Under rainfed conditions, the best time for planting is from September to November, after the first rains. Under irrigation, however, the best time for planting is from February to April. Sugarcane cultivation requires the clearing of land, often done by means of burning and slashing in Malawi. Although there are varieties of sugarcane that bear seed, most commercial sugar operations use vegetative propagation in order to plant a new field with sugarcane. This involves the formation of seed-cane either from the previous year's commercial crop or preferably from a select field identified to be used solely as a source for seed cane. Seed cane can take the form of cane setts, settlings, or bud chips. Cane setts consist of a segment cut from the stem of an immature cane stalk. The stalk is cut so that it includes 3 buds – or joints in the stalk – and it is from these buds that roots and shoots will grow. Three bud setts have been shown to have a higher percentage of germination than setts with more or fewer buds. Bud chips are a small portion of stem with just one bud. These are used to raise settlings in a nursery. Settlings are cane setts that have undergone germination and have grown roots and shoots.

This similarity of propagation with both potatoes and cassava means that a potential grower of sugarcane can source seed cane from a relative, neighbour, or even from Illovo who will have high quality, treated seed cane. This has two major benefits. The first is that a farmer without access to capital can trade labour – Ganyu – in exchange for cane setts from another grower. This reduces the capital requirement of commencing sugar operations. The second is a result of the presence of Illovo and that Illovo has a vested interest in obtaining more cane and higher quality cane. This means that prospective outgrowers can obtain seed cane along with the required inputs in the form of a loan which will then be deducted from his payment upon delivery of the cane.

After the ploughing of ridges and furrows, seed cane is planted and covered with soil. Ridges and furrows are especially important in soils that are not well drained as waterlogged soils are not suitable for sugarcane growth. When hand planted, row spacing is 1 – 1.3m and 1.4 – 1.6m when mechanically planted (Department of Agriculture Forestry and Fisheries, 2014). Plant spacing is 0.5m and soil covering should be 50mm in a furrow depth of 100mm.

Multiple crops can be grown from a single planted crop. Sugarcane is harvested by cutting the stems just above the ground after which the plant will regrow. This is called a ratoon crop. Fertilizer application differs for the ratoon crops and the planted crops and differs based on location. Typically, however, sugarcane requires 100-200 kg/ha of nitrogen, 10-60 kg/ha of phosphorous, and 100-175 kg/ha of Potassium (Department of Agriculture Forestry, and Fisheries 2014). After each harvest new stalks will grow back, however, with each successive ratoon crop the yields will decrease and eventually advocate for the planting of an entirely new crop. Commercial farmers typically grow between 2 and 10 ratoon crops. Sugarcane yields in Malawi under rainfed, surface and pivot irrigated conditions are 50, 107, and 140 tons/ha respectively (Agboma, Msuya, Tafesse, Kanu & Soliman, 1999).

Farmers are paid based on both the tonnage of cane that is delivered and the sucrose content of their cane. Malawian smallholder farmers have achieved sucrose levels of over 14% which is high. Growers receive a payment according to the cane supply agreement where growers receive 60% of divisible proceeds from both sugar and molasses sales (Corporate Citizenship, 2014). The divisible proceeds are calculated by the gross tonnage and sucrose content and for the 2012/13 growing season averaged 445 South African Rand (ZAR) per ton. This equates to US$ 50 per ton cane.

Sugar is now one of Malawi's biggest exports, second only to tobacco, and recently eclipsing tea for second place. Illovo is the sole producer of sugar in Malawi and over half of the sugar produced is sold to the domestic market while the remainder is sold to the European Union (EU) under the Everything But Arms (EBA) arrangement (Corporate Citizenship, 2014). In the 2012/13 season, this amounted to foreign revenue earnings of ZAR 730 million and accounted for 40% of the total sales revenue for the year. Of this, 25% of the total sales revenue was obtained through exports into the EU preferential markets. Sugar exports are now valued at US$ 61 million in Malawi which is double the value of sugar exports in the year 2000 of US$ 28 million when sugar was still the 3rd biggest export by value (FAO Commodities and Trade Division, 2003).

Despite Illovo's monopoly over Malawi's sugar market, prices are low. The company states that it does not abuse its power and that prices are in fact lower in Malawi than sugar prices in neighbouring countries. Furthermore, the company guarantees a nationwide fixed price and thus subsidizes distribution costs so that those in remote areas are not subject to exorbitant sugar prices (Corporate Citizenship, 2014).

In 2012, Illovo started fortifying all the sugar sold for direct domestic consumption with vitamin A in partnership with a UNICEF sponsored government initiative to combat high levels of vitamin A deficiency in the country. It is thought that this initiative will aid in reducing infant and maternal mortality rates in Malawi and it has been found that a similar initiative in neighbouring Zambia (also facilitated by Illovo) has improved the vitamin A levels of Zambian children significantly (Kafwembe, Chipipa, Njunju & Chilengi, 2009).

2.8 Modelling

Choosing and defining the modelling methodology to be used requires a review of different modelling techniques and tools available. A large variety of food security related models were reviewed in **section 2.5.3.** It was found many models measured food security without modelling food security dynamically. It was also found that the level or scale of these models was large. All scales were at the national or multi-national level while none were modelled at the regional or household level. Earlier, in **section 2.5.2**, a review of a selection of important modelling attributes was provided. The model type, or the model definition, is a function of the sum of these attributes and how they are chosen but also the chosen medium in which the modelling takes place. When selecting a model medium, model attributes are important to consider to some degree, however, there are a range of other factors that must be considered.

Important considerations, as adapted from (Brooks & Tobias, 1996), include:

- Whether model outputs adequately describe the behaviour of interest.
- The accuracy of results or predictions of behaviour.
- The ease which with the model and model results can be understood.
- Transferability and integration (the degree to which a model could be used by another or be integrated with other models).
- The probability of containing errors.
- Accuracy (model fitting with historical data).
- Theoretical basis strength (input data quality).
- Time and cost to run and analyse model.
- Hardware requirements for running the model.

A system is a collection of parts that interact with one another to function as a whole. A system, however, is not merely the sum of its parts but rather it is the product of their interactions (Ackoff, 1999). Analysis of a system requires systems thinking. Systems thinking is an approach to understanding change and complexity through the analysis of dynamic cause and effect over time (Maani & Cavana, 2007). Systems thinking acknowledges circular causation where a single variable both affects and is affected by another variable. In this way, it functions as both cause and effect within a system. Systems thinking recognises the primacy of the whole and appreciates that complexity can lead to unexpected and unpredictable system behaviour (Haskins, Forsberg, Krueger, Walden & Hamlin, 2006). Complex systems are often characterised by non-linear relationships and multiple interactions such as feedbacks (An, 2012).

Malawi's agricultural sector is large and one cannot decisively say how a single disturbance, let alone multiple disturbances, might impact the system. Furthermore, the agricultural system is by no means isolated. It is interlinked to infrastructural development, industry, government, weather systems, the global market and foreign policies. Despite this, decisions concerning the development of ICs must be made at both household and national levels. A framework or tool, therefore, must be employed to advise policy if sustainable growth is to be achieved and future food crises averted because of industrial crops.

The stakes are too high to discover the best way forward through trial and error. Furthermore, results of decisions made today might inadvertently lead to disastrous consequences only experienced many years down the line. On the other hand, implementation of the correct policy could lead to a secure, prosperous future. It is proposed that a computer model is built in order to:

i) quantify the impact of ICs on food security within Malawi;
ii) forecast and predict how IC policy might impact food security in the future through the use of scenarios;
iii) deepen understanding of the socio-agricultural system including determinants and feedbacks;
iv) provide a tool that can be used to engage stakeholders at all levels;
v) provide an interactive tool for policymakers to test decision implications;
vi) act as a focal point for guided discussions and debate – all in aid of a future that is more food secure for the smallholder farmers in Malawi.

Naturally, a modelling technique that can cater for the proposed outcomes, as stated above, that excels in the realm of complex systems and systems thinking must be used. It is thought that one of the major challenges to this endeavour will be the need to incorporate qualitative data. The model will thus need to incorporate mixed data – where data is both quantitative and qualitative in nature. There is also a very real possibility that gaps will exist in the available and collected data. Some data will be obtained from governmental records and where SSA is concerned, it is best taken with a pinch of salt. Although every effort will be taken to ensure the accuracy and completeness of the data, a model that can accommodate information gaps, experiential knowledge and expert opinions would prove a major advantage (Mendoza & Martins, 2006).

A variety of different modelling techniques were considered. These included soft systems approaches, computable general equilibrium models (CGEs), agent based models, discrete event simulation (DES), and multi-criteria optimisation (MCO).

Soft systems approaches have been described as “more adequate for addressing complex problems dominated by issues relevant to and influenced by, human concerns and their purposeful schemes” (Mendoza, Hartanto, Prabhu & Villanueva, 2002). An attribute central to the soft systems approach, and key to this project is structuring; which means that a model is arranged so that stakeholders, at all levels, can understand and hopefully engage in the decision and policy-making process (Mendoza

& Martins, 2006). Soft system methodologies include **cognitive mapping** and **strategic options development and analysis (SODA)**. Although cognitive maps and SODA are powerful tools in their own right, concepts are the building blocks of cognitive maps and they do not have the ability to manage quantitative data as required. Furthermore, the linkages in cognitive maps do not necessarily close and thus are not suited to the recurring and dynamic nature of the problem at hand (Maani & Cavana, 2007).

Computable general equilibrium models are a type of economic models that use realistic economic data to estimate how external disturbances might affect a market or specified set of markets (Sue Wing, 2011). It was determined the CGEs were not well suited to the problem at hand. This was primarily a function of two major issues. The first issue is that CGEs require a quality quantitative data set. Quantitative economic data is particularly hard to obtain for Malawi, one of the world's least developed countries, especially at the regional level. The second issue is that CGEs cannot run on qualitative data. As a purely economic model, social and physical systems cannot be modelled with CGEs. Something which is crucial to this study.

Agent based models are computerized simulations of a number of decision-makers or agents which interact through a set of prescribed rules (Bonabeau, 2002). Agent based modelling was ruled out primarily because there are not multiple instances of one agent that interact within the system or a set of rules that apply all agents. Instead there are a variety of different variables that interact with each other through exclusive relationships. In essence there is a distinct lack of agents in this problem but rather a single decision-making entity, the household.

Discrete event simulation models a system's behaviour in an ordered sequence of separate or disconnected events. DES is arguably the most widely used operations research (OR) technique in use (Brailsford & Hilton, 2001) and was deemed a potential candidate for use as the modelling medium for this study. However, DES's strength is in modelling entities as they pass through a string of activities and is most commonly used as a tool to model systems that resemble a queueing network (Brailsford & Hilton, 2001). The social, economic, and physical systems that need to be modelled in this study are a continuous system in real life. If a manner can be found to model the system continuously it would naturally be preferential.

Multi criteria optimisation is a field of multiple criteria decision analysis (MCDA) that is concerned with mathematical optimisation problems involving a number of objective functions that must be solved simultaneously in the quest for an optimal solution (Miettinen, 1999). Two major issues were identified with MCDA for use in this study. The first is that MCDA is mathematically intensive and cannot be used for soft modelling, that which makes use of qualitative data. The second is that it is a poor tool in itself to be used for stakeholder engagement and the methodology lacks an accompanying illustrative conceptual modelling step that can be used to such ends.

System dynamics is a mathematical modelling technique to understanding complex systems over time, especially systems that exhibit non-linear behaviour (Maani & Cavana, 2007). System dynamics is used pervasively for policy analysis and design. SD models solve the issue of simultaneity as a result of mutual causation. System dynamics is a continuous modelling technique and has the ability to incorporate qualitative data. System dynamics was determined to be the modelling technique best suited to the task at hand.

System dynamics offers a methodology that can cater for both hard and soft approaches. It has a core of mathematical dynamic modelling based on quantitative data but still allows for qualitative inputs (Maani & Cavana, 2007). Relative simplicity and transparency in comparison to other hard and more rigid models such as multi-criteria decision analysis (MCDA), agent-based, and mathematical models that are algorithm intensive allow for user transferability, model integration, and the involvement of stakeholders at all levels (Mendoza & Martins, 2006). Furthermore, the system dynamics modelling methodology incorporates a scenario planning and modelling step which allows for the running of a number of scenarios based on a variety of possible policy decisions that affect human controlled inputs. Scenario planning can cater for all types of 'what if' situations that could prove far more insightful than the pursuit of a singular numerical optimal solution for any given problem.

System dynamics also allow for a model that not only provides visible results and graphics upon the completion of the model but while under construction as well. It is a highly iterative process and will prove interactive and useful as a tool to be used for mediated modelling (Van den Belt, 2004). All in all, it offers a dynamic and inclusive approach which leads to logical, defensible, and explainable decisions. This makes system dynamics the modelling technique of choice for this project.

2.9 Conclusion

A review of food security definitions, indicators and measurements observes that the current definition proposed at the World Food Summit (1996) requires further refinement if it is to be used as the basis for a computer model. This study shows that food security is a function of both undernourishment and undernutrition and this proves more measurable and apt for use in the computer modelling arena. A conceptual review of opposing IC-food security arguments resolves that the role that ICs will play in aiding or hindering the advancement of food security is largely context specific and depends on upon social, agricultural and policy issues that are unique to a specific location. Therefore, this study concludes that a computer model should be built to better understand the relationship between ICs and food security and that this computer model should be one that is capable of scenario planning. A review of current food security models shows that current models are not dynamic and do not show, let alone explain, feedbacks within the system. Furthermore, there are no dynamic food security models that focus on the relationship between industrial crops and food security and this has been identified as a knowledge gap. Criteria were identified, and a review of various modelling techniques found that system dynamics would provide the ideal modelling technique and methodology. System dynamics was chosen primarily for its ability to incorporate both quantitative and qualitative data. It was also chosen because it will provide a tool that can be used to engage with stakeholders at all levels - both during and upon completion of the model.

Chapter 3: Methodology

In the previous chapter, it was proposed that system dynamics be used as the modelling methodology and medium for the creation of a systems-based model. This chapter aims to convey the methodology that will be followed for the duration of this study. However, even within the systems dynamics discipline, there exists multiple, albeit similar, approaches available. In this chapter, different methods of applying system dynamics will be presented and the methodology for the remainder of the study will be provided.

Systems dynamics methodologies are proposed by Maani and Cavana (2007), Albin and Forrester (1997), Randers (1980), Richardson and Pugh (1981), and Sterman (2000) and the various steps proposed by each of them have been outlined in **Table 2.1**. **Table 2.1** has been organised to display steps similar in nature in each row. Furthermore, columns display steps in the order suggested they be followed by each author.

Table 3.1: *Review of System Dynamics Methodologies*

(Maani & Cavana, 2007)	(Sterman, 2000)	(Randers, 1980)	(Richardson & Pugh, 1981)	(Albin & Forrester, 1997)
Problem structuring	Problem articulation	Conceptualisation	Problem identification and conceptualisation	Conceptualisation
Causal loop modelling	Formulation of dynamic hypothesis			
Dynamic modelling	Formulation of simulation model	Formulation	Model formulation	Formulation

	Testing	Testing	Model testing and further development	Testing
Scenario planning and modelling	X	X	X	X
Implementation and organisational learning	Policy design and evaluation	Implementation	Policy analysis	Implementation

A review of the different steps covered by the different methodologies proposed reveals that some steps in the process are distinctly common to all, some are implicitly present in all, and others are exclusive to one methodology. Maani and Cavana (2007) and Sterman (2000) both choose to split the act of problem structuring or articulation from that of the causal loop modelling step while Randers (1980), Richardson and Pugh (1981), and Albin and Forrester (1997) choose to integrate these steps. Nevertheless, problem structuring, and causal loop modelling are considered important inclusions by all authors and these steps will serve as steps one and two of this study.

Dynamic modelling naturally constitutes a step in all methodologies where the aim is to construct a dynamic simulation. This is step three. With the exception of the methodology proposed by Maani and Cavana (2007), all other proposed methodologies include a distinct step for model testing. While the methodology followed by Maani and Cavana (2007) still contains rigorous model testing, it is performed in the dynamic modelling stage of the process. This study has opted to isolate the model testing and verification step from that of the dynamic modelling step in an effort to maintain a clearer and more transparent modelling process. Model testing will be step four.

Maani and Cavana (2007) include a scenario planning and modelling step. Remembering that one of the reasons system dynamics was chosen as the modelling medium was because of its ability to run a variety of scenarios, a full step in the process dedicated to scenario planning and modelling is appropriate. Scenario planning is particularly important in this study and will require structured thought owing to the high number of model input combinations that exist. Scenarios that are most valuable in understanding the system's unique dynamics or reveal results most impactful to generating policy discussion must be selected correctly. Therefore, this study included this step as step five in the methodology.

The final step, step six, incorporated in various manners and proposed by all authors, is that of model implementation and policy analysis. The steps chosen are a hybrid of the methodologies outlined above and are believed to encompass all the important aspects of the system dynamics procedure. A summary of the chosen path is provided in **Figure 3.1**.

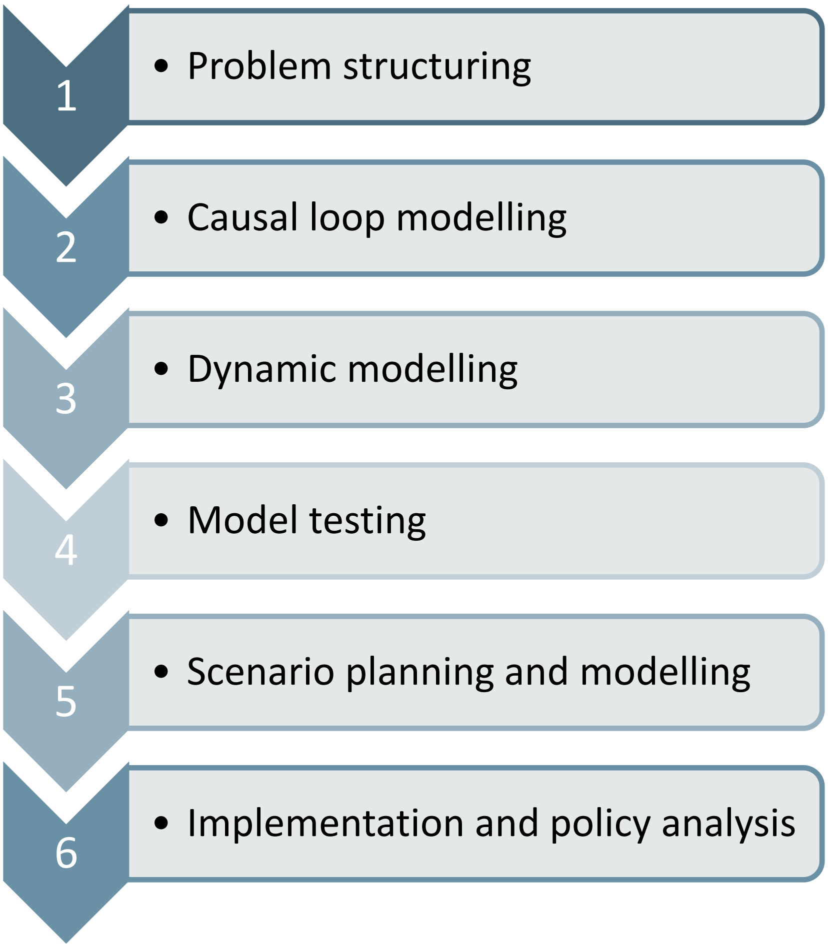

Figure 3.1: *Steps of the System Dynamics Methodology*

A brief description of each step is outlined below and has been adapted from Maani and Cavana (2007).

3.1 Problem structuring

The aim of this step is to identify, grasp, and define the problem or issue at hand. It is during this step that the real problem, or problems, must be isolated from problem symptoms. This phase can be broken down further into three more refined steps.

1. Identification of the problem area or policy issues of concern at the level of management. The main stakeholders and their interests must also be identified in this step. This requires established objectives.
2. The collection of preliminary information and data in the form of media reports, historical and statistical records, policy documents, previous studies, and stakeholder interviews necessary to clarify the magnitude and gravity of the problem.
3. The holding of group sessions to foster creative problem structuring and ensure the unique perspectives of the problem are captured effectively.

3.2 Causal loop modelling

Before construction of the rigorous algebraic model can take place, a conceptual model must be constructed. Causal loop diagrams (CLDs) are a tool for revealing the causal relationships that exist between different actors, variables, or factors in the system. CLDs, in their most basic form, consist of two main elements; variables and arrows. Arrows show links between variables. CLD variables are a representative of a measure. A measure can be qualitative or quantitative. This has been noted as a particular strength of CLDs, that they have the ability to incorporate qualitative variables in the systems thinking approach.

CLD arrows are representative of a relationship between two variables, and as such are drawn between two variables. CLD arrows are coupled with either a '+' or 's' sign to signal a positive relationship where variables move in the **s**ame direction or a '-' or 'o' sign to signal a negative relationship where variables move in the **o**pposite direction.

This step requires the identification of the main variables, construction of the reference modes for these variables, the construction of the conceptual model in CLD form, a discussion of the expected behaviour over time implied by the CLDs.

3.3 Dynamic modelling

The dynamic modelling phase is where the formal mathematical based simulation is constructed. Here variable types such as stocks (levels), flows (rates), converters, and constants are defined. To populate the model data are required.

The data are used to,

- provide values for constants,

- to define mathematical relationships for converters and rates,
- set initial values for stocks,
- and set the correct units for all model variables.

This step in the modelling procedure requires the use of a specialised system dynamics software package such as STELLA, iThink, VENSIM, POWERSIM, DYNAMO, COSMIC or Consideo. The computer package utilised in this study was VENSIM by Ventana Systems.

Initial values are chosen, the unit of time is specified, the simulation interval is selected, and the time horizon is then set. The completed model is then simulated over time. Graphical and tabular outputs are then produced for the base case (baseline scenario) and other chosen scenarios.

3.4 Model testing

The model testing phase is crucial in model construction if the simulation is to provide meaningful results. There are several steps that must be followed to ensure the model operates at the required standard. The first step is to verify the models structure. This step entails checking that the structure declared in the model exists in the real system. The second step is that of parameter verification. This involves ensuring that parameters or constants within the model correspond to those in the real system both conceptually and numerically.

The third step is that of extreme condition testing. This requires the model be subjected to inputs of very high, very low, and even negative values to ensure that the model remains robust under extreme parameters. The fourth step is that of testing for boundary adequacy. Boundary adequacy is essentially the opposite of the structure verification test. This step tests whether the model includes all relevant structure in the real system and whether the level of model aggregation is appropriate.

The fifth step is to test the model for dimensional consistency. This is achieved through a check functionality that is built into the software. In VENSIM, this includes both a 'units check' and 'model check' function. The sixth step is to check for adequate model reproduction of system behaviour. This is a check to determine whether the model reproduces the observed behaviour in the real system accurately. The final step is to check model sensitivities with regards to model behaviour. A summary of the path for model testing is provided in **Figure 3.2**. The methodological approach followed here is that which is recommended by Forrester & Senge (1980).

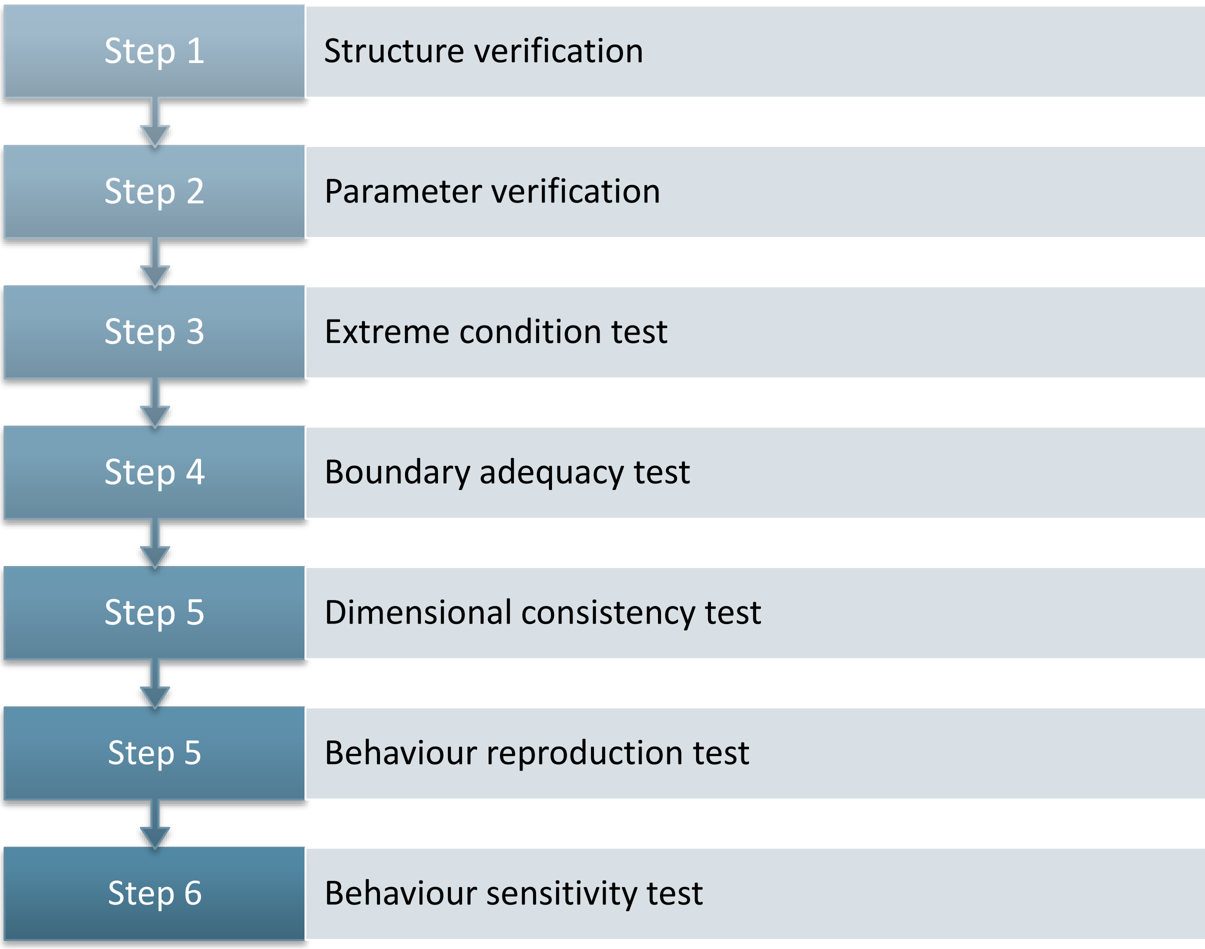

Figure 3.2: *Steps of Model Testing*

3.5 Scenario planning and modelling

This phase comprises of the formulation and testing of a variety of different policies and strategies. Maani and Cavana (2007) distinguish between policy and strategy. A policy is a change to a single internal variable while strategy refers to the combination of a set of policies. It is the testing of these strategies under varying external pressures that is referred to as scenario modelling.

In this step, one needs to prepare stories of possible future scenarios. One must then identify key drivers of change and uncertainties that might impact policies and strategies. It is in dealing with these uncertainties that scenario development proves critical in providing meaningful answers. Where key variables, sensitivity, and uncertainty overlap, various scenarios can be developed to answer a variety of what-if questions and provide the best case, worst case, and most likely outcomes.

3.6 Implementation and policy analysis

The final step is that of analysing the results of the various scenarios and preparing a report to deliver to the relevant stakeholders. Problem insights, results, and the proposed intervention or interventions need to be communicated to all stakeholders.

Chapter 4: Model development

4.1 Problem structuring

The problem structuring phase of the systems dynamics process begins with the identification of the problem area. The gap is then identified, this is the difference between the current and ideal situation. The dilemma is then outlined which explains the conflicting components of the system. Finally, the problem statement is provided.

4.1.1 Problem area

Recent land expansion into industrial crops in Malawi has caused concern that the already food insecure nation will begin to produce even less food. Malawi's smallholder farmers are thought to be most vulnerable to any major disturbances in Malawi's agro-economic system. Therefore, the problem area, the chosen study area for this project, is the Malawian smallholder agro-economic sector. Most simply, the aim of this study is to determine the effects that IC expansion might have on the food security of these smallholder farmers.

4.1.2 Gap

The ideal situation is that of complete food security for Malawi's smallholder farmers whereby "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" (World Food Summit 1996). Food security can be achieved either by growing sufficient food or earning enough money to ensure economic access to sufficient, safe and nutritious food. Unfortunately, the reality in Malawi is different. Malawian smallholder farmers are unable to grow sufficient food to meet the daily dietary energy requirements throughout the year and are unable to earn sufficient money to break out of the poverty cycle. The discrepancy between the ideal situation and the current situation is the problem gap.

4.1.3 Dilemma

The dilemma is that while ICs are a potential pathway for increased earnings for many Malawian smallholder farmers they require the diverting of arable land away from food crops. This undesirable trade-off between food production and cash earnings from ICs is the dilemma faced by many smallholder farmers in Malawi.

4.1.4 Problem statement

Malawi's smallholder farming sector is food insecure. The effect that a surge in IC expansion will have on smallholder food security is not known. Efforts to understand the possible effects of IC expansion must be made before the pervasive growth of various ICs can be encouraged or discouraged.

4.1.5 Model Boundaries

The model boundaries are set to define the scope or extent of the formal simulation model that is completed in the dynamic modelling phase. Potential variables within the system and those external variables that might affect the system are divided into three factions. Endogenous variables are those that will both affect and be affected by the system and will be wholly included in the simulated system. Exogenous variables are those that impact the system but are not impacted by the system, or at least not impacted by the system given the model assumptions or time horizon. Excluded variables can be both endogenous or exogenous variables in the real-life system but have been intentionally excluded from the model because they,

- Are deemed to have little or no effect on relative outputs (ie. If a variable affects two other variables under examination in the same way, in terms of both magnitude and direction, then the effect of the variable is trivial in the comparison).
- Are deemed not modellable given the modellers time and resources or software package.
- Drastically alter the model's extent and scope achieving a limited benefit in model fidelity which is not worth the increase in modelling effort with regard to time, cost, or computing power.

Table 4.1: *Defining the Model's Scope*

Endogenous	Exogenous	Excluded
Available cash	Climatic conditions (rainfall, drought)	International market trends
Food stores	Household size	Soil variability
Food supply	Access to credit	Labour
Fertilizer purchased	Required calories	Currency devaluation
Food losses	Off-farm income	Purchase of luxury items services
IC income	Land cultivated	Inflation

Acquired loans	Minimum off-farm expenses
Debt repayments	IPS & trust membership
Input expenses	Cropping cycles
Food purchased	Crop partitioning
Food sold	Input costs
Household consumption	Tobacco & sugarcane price
Fertilizer in use	Interest rates
Crop yields	Maize subsidies
Irrigation	

4.1.6 Reference modes

Before embarking on the dynamic modelling phase of the system dynamics procedure it is good practice to construct behaviour over time (BOT) graphs that capture the expected model behaviour of certain variables within the system. These are known as reference modes. A benefit of constructing reference modes is that they can be used as a method of model validation in the case of the model outputs imitating the reference modes. Furthermore, through the modelling process of constructing both the CLDs and the dynamic model, the modellers understanding of the system can and, most likely, will evolve. Capturing the modellers expected outcomes, before the modelling process begins, is valuable in the comparison of how the system was thought to behave versus how it does behave. Therefore, where model outputs differ from the reference modes the reference modes provide a valuable tool in showing the evolution of the system understanding.

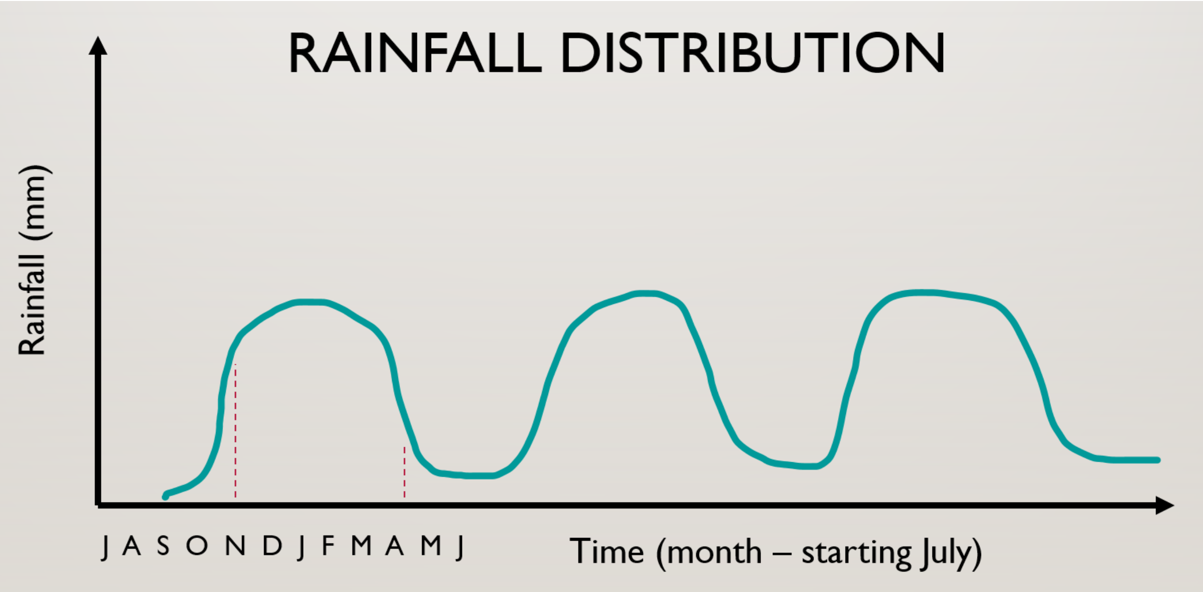

***Figure 4.1**: Reference Mode of Rainfall Distribution*

The modeller expects the rainfall in Malawi, which is known to be seasonal, to behave according to that which is shown in **Figure 4.1**. Here, the rainy season is expected to begin in November and end in April, with the wettest months in between. The rainfall is also expected to vary between the same months of consecutive seasons, with total rainfall varying between seasons.

***Figure 4.2:** Reference Mode of Food Consumption when Food Secure*

With the planting of sufficient land with either food crops or ICs, the modeller expects a smallholder farming family to be able to maintain a caloric intake equal to or above the minimum daily dietary requirement of 2400 calories as recommended by the FAO. The modeller expects this to be maintained with the planting of roughly 0.8 hectares of land or more, considering normal climatic variability.

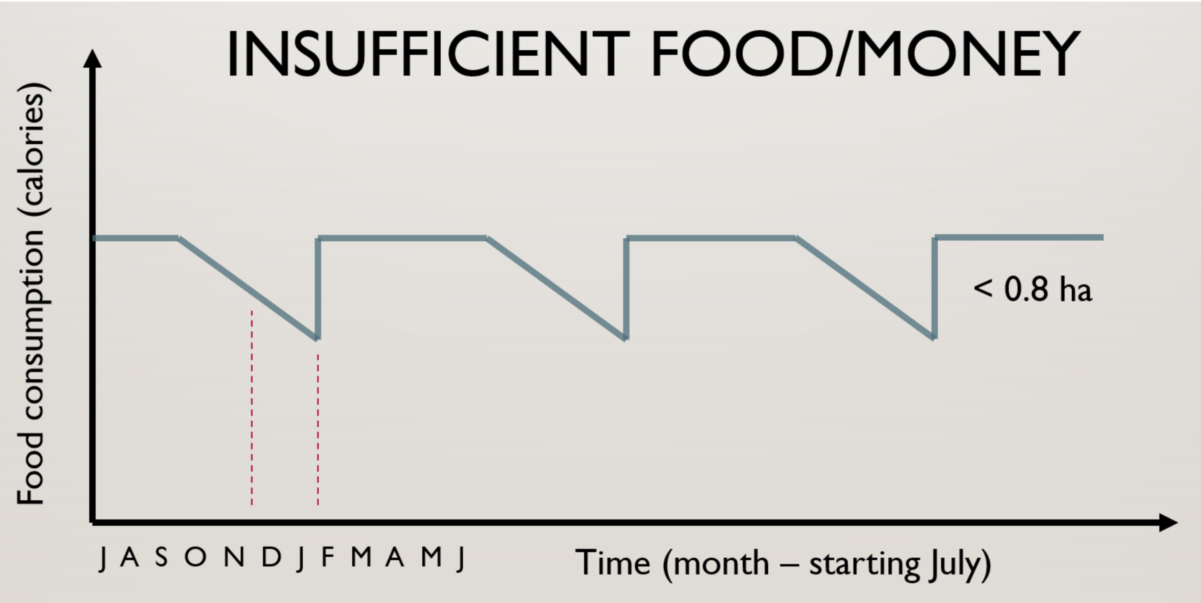

Figure 4.3: *Reference Mode of Food Consumption when Food Insecure*

The modeller expects that in the case of a smallholder farming family planting less than 0.8 hectares of land with either food crops or ICs that the desired consumption of 2400 calories per person per day will not be sustained. In the case of insufficient food or money to buy food it is expected that the household will begin rationing food until the next harvest. The modeller expects that smallholder households are likely to experience months of extreme hunger in the months of December to late February or early March. Rationing is only expected to take place a few months after the harvest.

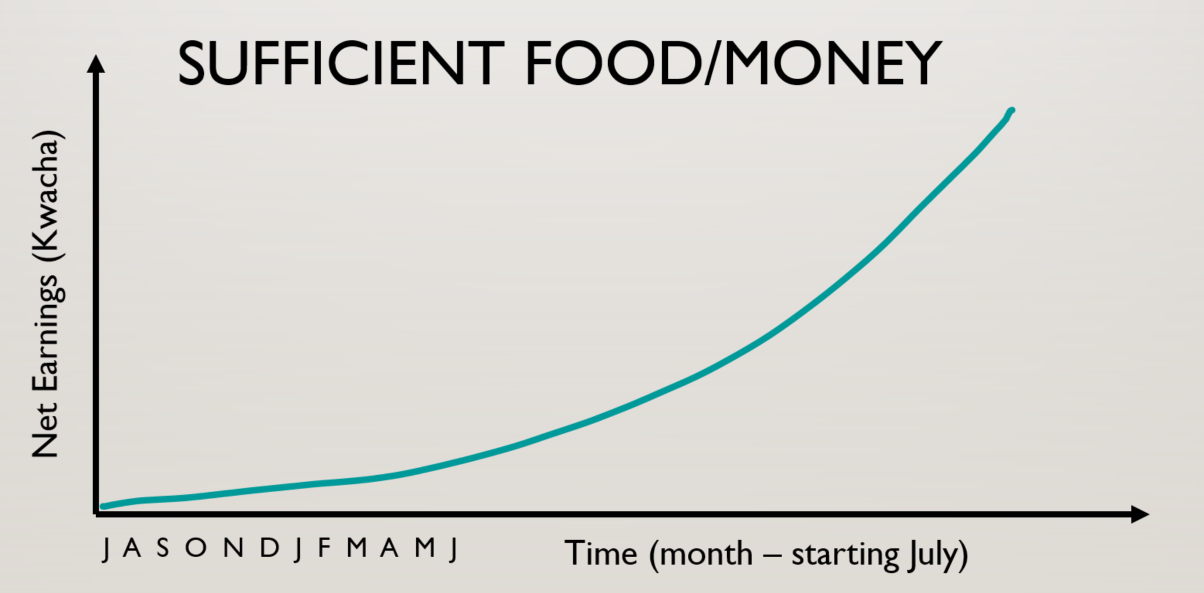

Figure 4.4: *Earnings when Food Secure*

Those smallholder farmers who plant above a certain threshold of acreage are expected to build wealth over time. The growth in wealth is expected to be exponential, starting slow and accelerating with over time horizon.

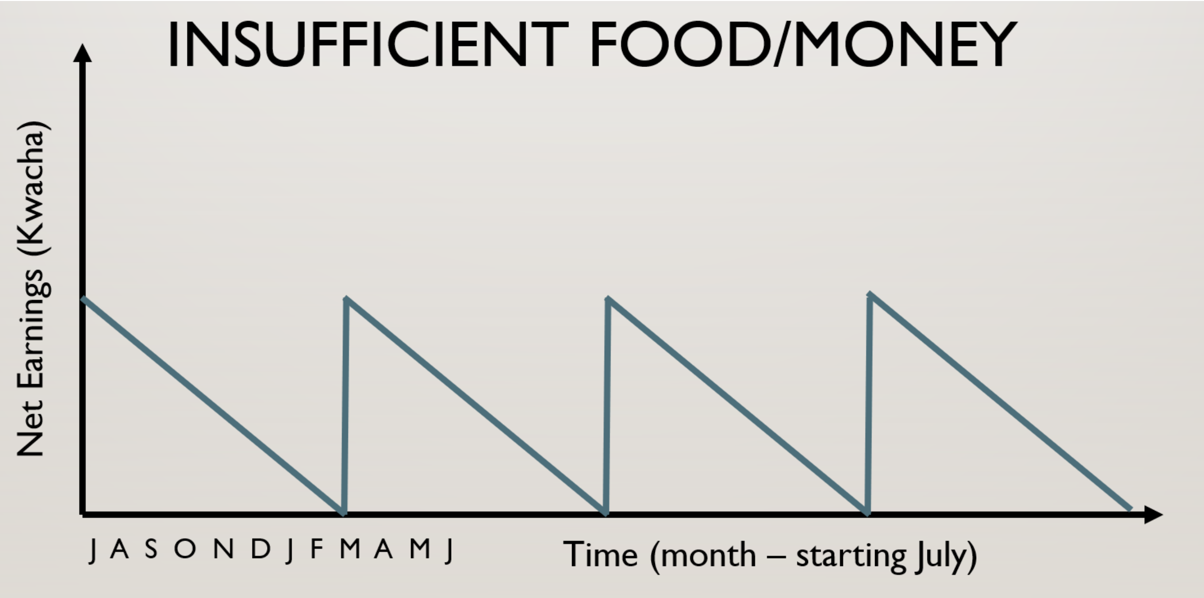

Figure 4.5: *Earnings when Food Insecure*

Smallholder farmers planting below the threshold of land needed are expected to burn through their total food or cash reserves. The curve is expected to be characterised by surges in wealth during months of harvest followed by a steady decline as acquired resources are used up.

4.2 Causal loop modelling

The final step before the formal simulation phase commenced was the formulation of a conceptual model. A conceptual model is helpful in system understanding. In system dynamics, CLDs are used to map the conceptual model. Causal loop modelling is the most commonly used phase of the systems dynamic approach and the process of creating CLDs is one of the defining steps of the system dynamics procedure. CLDs are a tool for revealing the causal relationships among a set of variables or factors which operate in a system (Maani & Cavana, 2007). Components of CLDs and their usage are provided in **Table 4.2**.

Table 4.2: *Tools of Causal Loop Modelling in System Dynamics*

Type	Meaning	Identifier
Variable	Quantitative or qualitative elements within a system	variable name
Arrow	Indicates causality between two variables	→
Positive causal association	Indicates variables move in the same direction	+
Negative causal association	Indicates variables move in opposite directions	-
Delay	Signals a delay in the effect one variable has on another	─╫→
Feedback process	Defines whether a feedback loop is reinforcing or balancing	(R) (B)

4.2.1 Simplified conceptual model

The agricultural and socio-economic system in which smallholder farmers in Malawi operate is captured in **Figure 4.6**. The CLD is a simplified representation of reality and is used to delineate those aspects of the real-life system that are deemed central to the problem as defined in the problem definition. The CLD for the Malawian smallholder farming sector is from the household perspective. This is done in preparation for the creation of a simulation at the household level and consists of seven interdependent feedback loops. The CLD conceptually models the different drivers of food security. Five feedback loops are reinforcing, two are balancing.

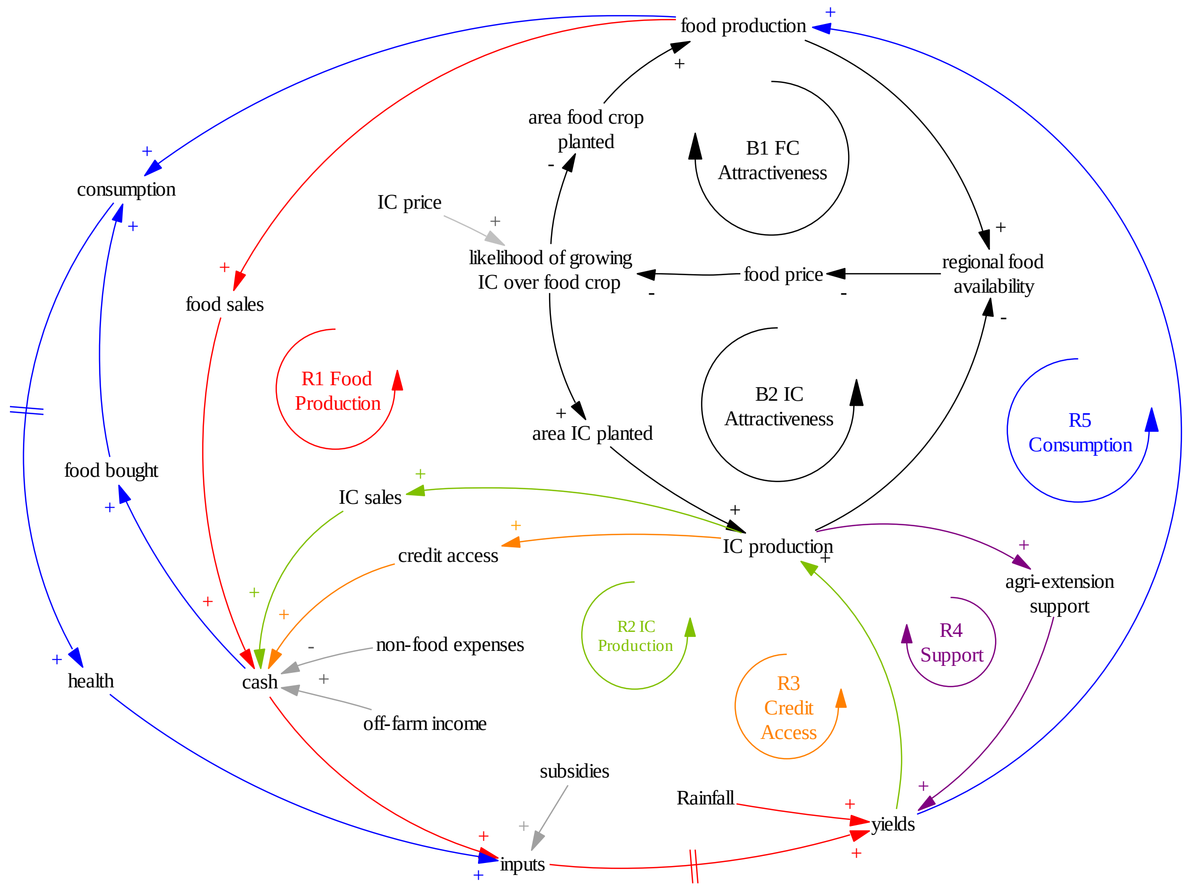

Figure 4.6: Simplified System Representation CLD

4.2.2 Food and industrial crop production feedbacks

The first two feedbacks loops are those of food and IC production respectively. The feedback loops are both reinforcing. The formation of growing or declining trends over time is largely dependent on two factors.

The first factor is the net return on investments made. In both cases, a farmer who has at least some quantity of money can afford to buy at least some inputs. Inputs consist of purchased labour, fertilizer, chemicals, and irrigation. The inputs purchased amount to a certain value of money and as a response to this purchase, yields and total food and IC production are expected to increase by some measure. The return on investment is equal to the realised increased production value relative to that which was invested into inputs. If the increase in the value of production does not match or exceed that which was invested, then cash reserves will decline over time. In the case of the opposite being true, cash reserves will grow. Naturally, both increases in food production and cash reserves have a positive relationship with consumption and ultimately food security. These pathways to food consumption have been incorporated in the feedback loops in **Figure 4.7**.

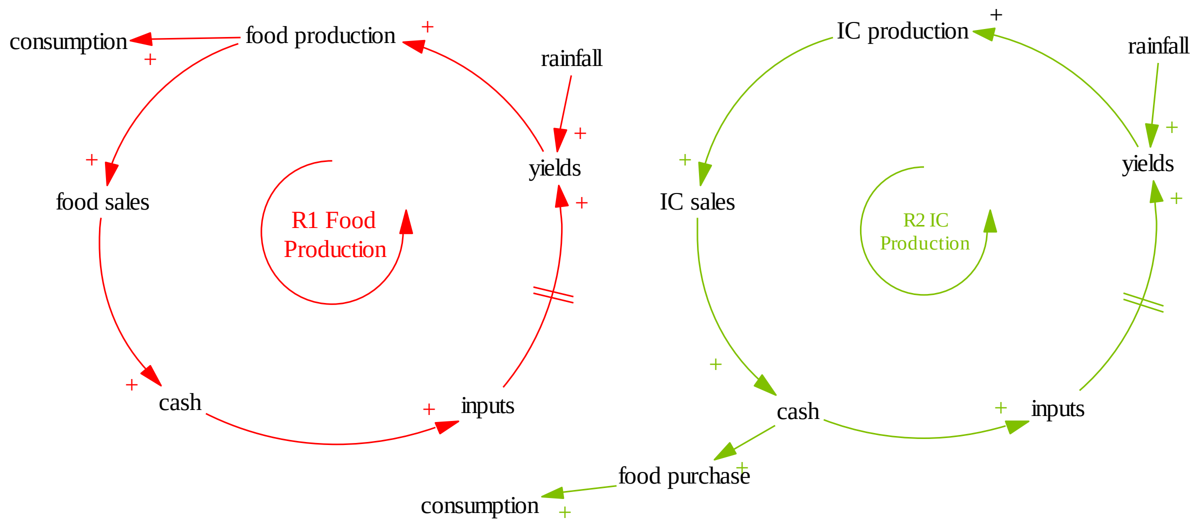

Figure 4.7: Food and IC Feedback Loops

The clear majority of smallholder farmers in Malawi do not irrigate. In the absence of irrigation, rainfall is another significant factor dictating whether these feedbacks form growing or declining actions over time. With rainfall providing considerable variability within the system, crop resilience becomes an important factor in determining overall success (a growing trend) or failure (a declining trend). The relationship between rainfall and crop yields present an interesting dynamic. On one hand, crops with a high response to rainfall would return large yields when the value of the rainfall variable is high, evoking feedback loops strongly reinforcing in the positive direction. On the other hand, these same crops, being sensitive to rainfall quantities, might also prove far less resilient to system shocks induced by drought. Food and IC crop performance over time can therefore not be discerned from the CLD alone. This further advocates for the construction of a dynamic simulation.

4.2.3 Credit access and support services feedbacks

Engaging in IC production activates the third and fourth reinforcing feedback loops shown in **Figure 4.8**. Those smallholder farmers who engage in IC production have increased access to credit facilities and agricultural support. In the case of sugarcane and tobacco growing, it is the sugar trusts and leaf companies respectively that provide loans, often in the form of inputs, to farmers. Those only involved in independent food production have very limited access to credit and capital, what access that is had is often at the mercy of loan sharks offering loans at extremely high interest rates.

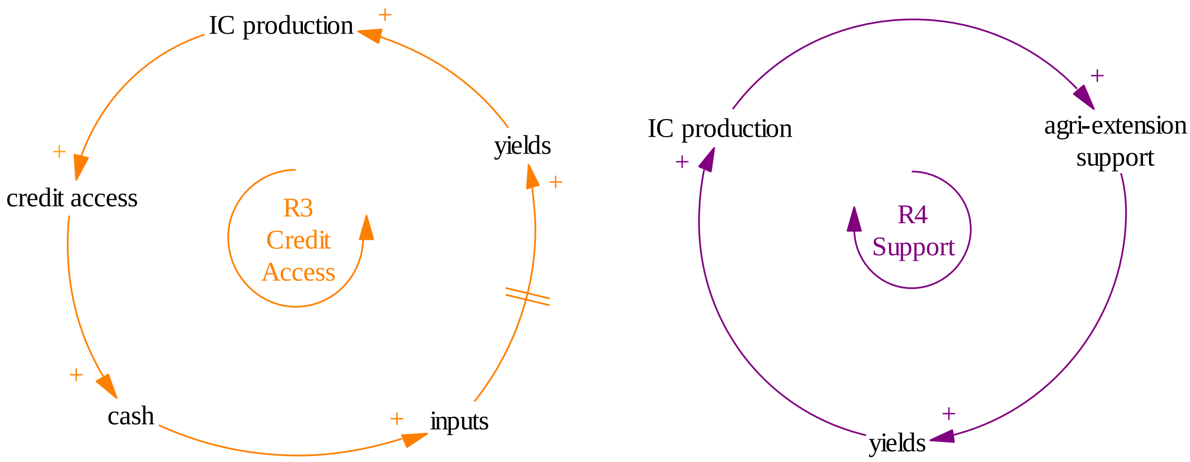

Figure 4.8: *Access to Credit and Support Services Feedback Loops*

Farmer's engaged in IC production have better access to knowledge support. In particular, those farmers that are involved in either IPS contractual arrangements with the tobacco leaf companies or that constitute part of the sugarcane trusts are positioned to receive additional support. This is owing to the vested interest that both the leaf companies and sugar trusts have in ensuring the quality of product delivered to them for processing. Entirely independent tobacco growers do not receive similar access to support from private leaf companies. These farmers, however, receive support from ARET. ARET provides agricultural support through a network of agricultural extension officers.

4.2.4 Consumption feedback

The final reinforcing feedback loop captures the effects of sufficient or insufficient long-term consumption, see **Figure 4.9**. An insufficient diet with regard to quality, quantity, and diversity will affect farm production. The cumulative effect of household members repetitively not meeting their required DER leads to declining health and ultimately a shortage of labour. The average household in Malawi consists of 4.6 members (NSO, 2012) and the effect of a household member becoming too weak to work, or becoming less efficient, can greatly impact farm productivity. This is most apparent concerning tobacco, which is highly labour intensive and has less impact on those who farm sugarcane, which is a ratoon crop and is often managed by a trust. The effect of consumption on health has been delineated as a delayed effect moving in the same direction. This translates to an increase or decrease in consumption leading to an increase or decrease respectively in a household's health with a delayed effect. The delay assumes that a single missed meal will not affect a household's health, but a long-term drop in consumption will eventually lead to adverse health effects in the future.

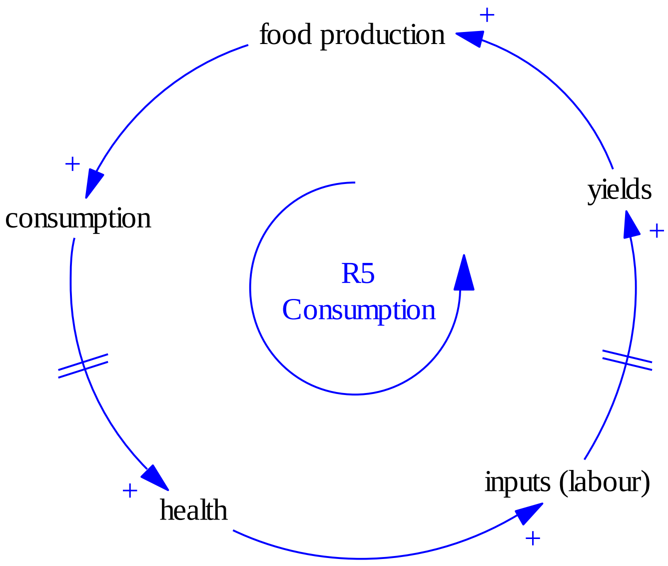

Figure 4.9: *Consumption Feedback Loop*

4.2.5 IC attractiveness feedback

Figure 4.10 is a composite of two feedback loops. Both are balancing. The loops are based on two assumptions. The first assumption is that the relative attractiveness of growing ICs is dependent on the comparative difference between staple food prices and the prices fetched for industrial crops. The second assumption is that the prices fetched for industrial crops remain largely consistent relative to regional staple food prices, which fluctuate greatly within the season, and year on year. Some degree of price fluctuation is present within the sugar and tobacco sectors but is largely protected through sector regulation. If farmers plan to grow either tobacco or sugarcane in the upcoming season, they must obtain a quota to do so. Regulating supply in this manner ensures that demand is not exceeded. This allows prices to be maintained to some degree. No effective regulation in food cropping and production results in wild differences between supply and demand. This drastically affects food prices throughout the season and year. Naturally, increased food production leads to an increase in regional food availability and a drop in staple food prices. Lower food prices increase the attractiveness of growing ICs.

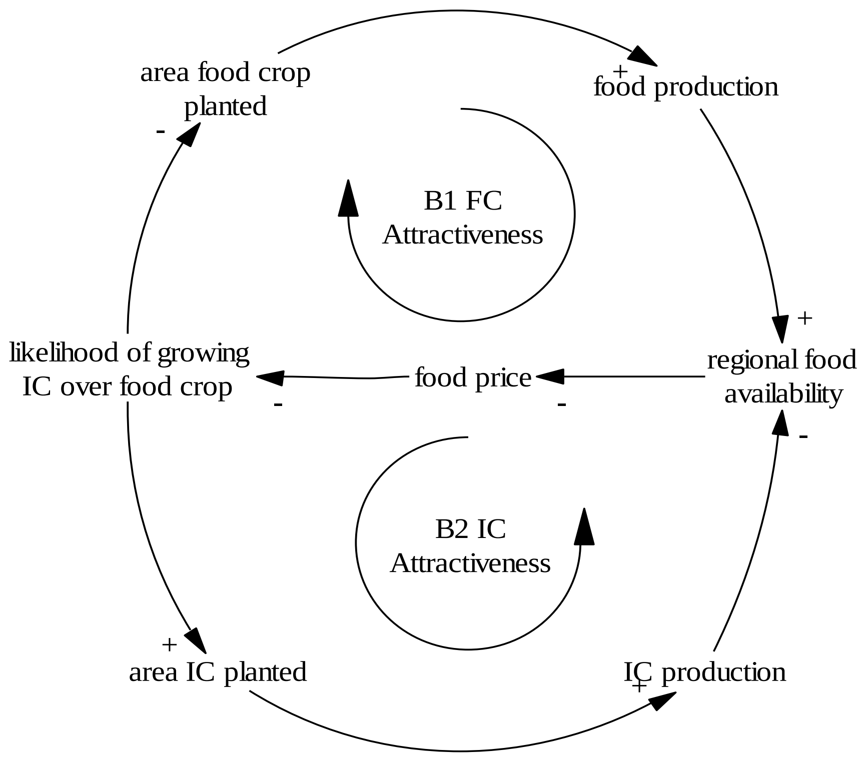

Figure 4.10: *Attractiveness of ICs Feedback Loop*

It is important to note that the food price affects the attractiveness of growing ICs in two ways. Higher food prices mean that growing food will return a higher income for the farmer. Higher food prices also mean that a farmer engaged in IC production will have to spend more money when purchasing food. This demonstrates that changing food prices affect farmer decisions from both a profit and cost perspective having double the impact.

Both loops are balancing. Balancing loops cause oscillating behaviour until a point in time at which equilibrium is reached. Should this indeed be the picture, these balancing loops imply that the agriculture sector would eventually stabilize, and the prices and land area given to each crop would remain constant at the regional or national level. In Malawi, which is almost entirely dependent rainfall for crop irrigation, food production and regional food availability will continue to vary subject to climatic conditions and equilibrium is unlikely to be reached. From this initial analysis using the CLD, it is postulated that the problem is not with the introduction of industrial crops but rather a lack of investment into irrigation.

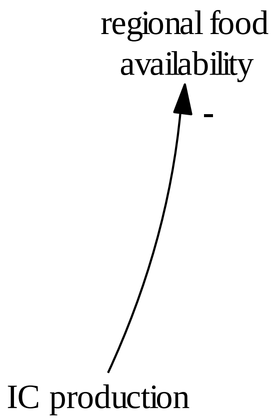

Figure 4.11 *IC production to regional food availability pathway*

In **Figure 4.11**, the relationship between IC production and regional food availability is isolated. IC production and regional food availability have been designated to move in opposite directions and have been given the negative sign. This is the superficial view. The relationship between these two variables is complex and central to this study's investigation. Potential pathways to move from IC production to regional food availability are summarised in **Table 4.3**.

Table 4.3: *Potential Pathways from IC production to regional Food Availability*

IC production means:	Which leads to:	Effect on food availability
Arable land used for ICs	Less land used for food production	-
Higher monetary earnings	Increased inputs available for food crops in addition	+
Access to capital (when in input form)	Increased inputs available for food crops (diversion of inputs from IC to food crops)	+
Increased income with limited increase in labour demand (sugarcane only)	More intensive food crop farming owing to labour availability	+
Development of infrastructure	Higher prevalence of irrigation	+
Land can become unsuitable for food cropping	Land not returned to food production	-

Aspects of these pathways shown in **Table 4.3** can only be effectively modelled at the regional scale and therefore fall outside the scope of the dynamic model. For example, a household level model will not capture the total national transfer of land from food crops to ICs and associated loss in total food production under the given input parameters. However, a model at the household level perspective can capture the difference in individual household food production for a variety of different scenarios which capture different levels of engagement in IC production and crop types. This is the strength of scenario development. Results from the comparison of various scenarios can be used for estimation of regional effects and trends through the process of upscaling. There are two potential pathways to achieve meaning at the regional or national level from household models. The first is through upscaling the results, the second is through upscaling the model.

Upscaling the results requires the use of the household level simulation results to provide unique big-picture insight through analysis. This can be achieved through the asking of certain questions. Examples of relevant questions would include,

- To what proportion of the population does this apply to?
- What would the effect be if the entire population to which this applies adopted each scenario?

The second pathway is the upscaling of the actual model. This needs to be exercised with caution as both upscaling and downscaling the spatial levels of models can have profound consequences (Rotmans & Asselt, 2001). The inherent difference between the approaches is that upscaling the results is a qualitative logical approach while model upscaling is quantitative. This study will use the first approach given the available resources and time, and to avoid potential pitfalls or inaccuracies associated with model upscaling.

4.3 Dynamic modelling process

The model simulates smallholder farming in Malawi from the household perspective. The system dynamics (SD) model was built in the Vensim software package. The professional (DSS) version was used on license to Stellenbosch University from Ventana Systems Incorporated. The Euler method of integration was selected for the model. The time step was set at 1 and results were saved every time step. The units for time were set to months and the model was run for 15 years.

4.3.1 Model attributes

With reference to **section 2.6.2,** titled a **review of modelling attributes,** model attributes were selected to best address the issue at hand as described in the problem statement.

The **level of analysis** was selected as a micro-level of analysis. In this case, micro-level perspective translates to analysis at the household level. Household level analysis was chosen to perceive problems and find solutions from the perspective of the household in an effort to put the smallholder farmer first. Models at higher levels of analysis tend to find regional or national solutions for regional or national problems without accounting for the micro-level system intricacies. This bottom-up approach aims to understand and incorporate these intricacies into the model.

In terms of **cross-scale dynamics**, the model's extent or scope includes only those smallholder farmers that have the option of growing either sugarcane or tobacco or both in addition to any of Malawi's staple food crops. While Malawi's tobacco farmers are dispersed throughout the country, although notedly the majority are concentrated in Malawi's central provinces, for the growing of sugarcane, smallholder farmers must have access to land within a 50km radius of the three sugar mills. There are two sugar mills in central Malawi and one mill in southern Malawi.

The model's spatial resolution is measured in hectares and operates in intervals of 0.1 hectares. The model's temporal resolution was set to months. Months was chosen owing to it being the largest time measurement able to appreciably incorporate seasonal fluctuations in rainfall needed to achieve the desired crop model accuracy. This temporal resolution also allows for household decisions to revisited monthly as the food security or income situation changes.

The inclusion of **temporal dynamics** allows for the model to incorporate path dependency as its own driving force. Other **driving forces** are addressed in the explanations of the sub-models. The outcomes of this model are path dependent. As previously discussed, this raises the issue of model validation. Model validation is addressed in **section 4.4**.

The model follows the second approach as outlined by Verburg *et al.* (2004) whereby the focus is on the interactions between the sub-systems rather than on the sub-systems themselves. This is a high **level of integration**.

4.3.2 SD modelling tools

SD modelling makes use of several standardised tools regardless of the software package chosen. The tools available to the modeller are outlined in **Table 4.4**. There are six model components available for the construction of an SD model.

Table 4.4: Tools of System Dynamics Simulations

Type	Meaning	Identifier
Stock (Level)	Cumulative – Integral over difference in rates	level
Flow (Rate)	Flow of material over time	Rate ⧖
Auxiliary	Model variable – defined by equations	model variable
Constant	Independent (not necessarily fixed)	constant
Shadow variable	Allows interlinking while maintaining visual order	<shadow variable>
Arrow	Delivers a variable for use in the definition of another	→

4.3.3 Sub-models

Theoretically, there is only one model. For organisational and explanatory purposes sections of the model have been grouped together into sub-models. There are six sub-models that interact with each other to simulate smallholder farming in Malawi from the household perspective.

4.3.3.1 Rainfall

The aim of the rainfall sub-model is to simulate rainfall in Malawi with sufficient accuracy regarding both quantity and variability. Rainfall data were obtained from the Malawi Meteorological Services (2017) in Blantyre. Data were obtained for twelve rainfall stations across five districts in Malawi. The districts were chosen because of the high prevalence of growing ICs there.

Table 4.5: Distribution of Rainfall Data

District	Stations	Primary IC grown
Nkhotakota	Nkhotakota, Dwangwa	Sugarcane
Chikwawa	Ngabo, Chikwawa, Nchalo	Sugarcane
Kasungu	Kasungu, Mwimba	Tobacco
Mulanje	Mimosa, Boma	Tea
Thyolo	Bvumbwe, Thyolo, Masambanjati	Tea

The rainfall data for Dwangwa were selected owing to the presence of a sugar mill within the area, a particularly high prevalence of cassava and potato farming in addition to maize, and its proximity to areas of high tobacco cultivation. Rainfall data are interchangeable and can be tailored according to the chosen scenario. The baseline scenario uses the rainfall specific to Dwangwa. Rainfall is recorded and documented using a year that begins in July and ends the following year in June. This places the rainy season, which runs from November to April, firmly in the centre of the year allowing seasons to be adequately compared.

In all cases, the acquired data exists at least from the season of 1971/72. In some cases, the data extends back to the season of 1915/16. The data were acquired monthly for all years recorded. This allows for sufficient data to calculate meaningful averages, standard deviations, maxima, and minima per month for simulating model variability. To this end, within the model, the random normal function is called. The function receives the arguments as seen in **equation (4.1)**. The assumption made here is that the rainfall variability is normally distributed.

$$Rainfall_i = RANDOM\ NORMAL(\{min\}, \{max\}, \{mean\}, \{stdev\}, \{seed\}) \quad (4.1)$$

Where, i = January → December

Long-term variability owing to the effects of La Nina and El Nino climatic conditions is also simulated. The cyclic nature of El Nino and La Nina effects are modelled with the aid of a sine function. The function has a period typical of the average number of years in a cycle and magnitude allowing for an additional 20% variability. This allows for the possibility of an unlikely event such as drought or flood to occur. It also allows for the occurrence of years that are consecutively drier and years consecutively wetter as experienced in real life weather patterns. No stocks or rates were declared in the rainfall sub-model. Total monthly rain is returned as an output for use in other sub-models.

4.3.3.2 Food cropping

The food cropping model is concerned with the growing and production of three staple food crops; maize, cassava, and potatoes. There are three major drivers of crop production. Both the land-area given to a crop and the rainfall received are exogenous drivers. The inputs received as fertilizer for crop production is an endogenous driver. The sub-model contains three stocks. The three stocks track the amount of rainfall during each crop's growth period. Each of the stocks has two rates. The rates add monthly simulated rainfall (SR) to the stocks as rainfall in (RI). The rates out subtract that which falls outside of each specific crops' growing period or cropping cycle (CC) as rainfall out (RO).

Rate in: $$RI(t)_i = SR(t) \quad (4.2)$$

Stock: $$GSR(t) = GSR(t-1)_i + \int RI(t)_i - RO(t)_i \, dt \quad (4.3)$$

Rate out: $$RO(t)_i = FIXED\ DELAY(RI(t)_i, CC_i, 0) \quad (4.4)$$

Where, RI = rainfall in, SR = simulated rain, GSR = growing season rainfall, RO = rainfall out and, i = {maize, potato, cassava}.

The amount of fertilizer that can be afforded at the time of planting is returned from the inputs sub-model. The amount of the fertilizer purchased is used in conjunction with rainfall to determine the crop yield. The yield per hectare is multiplied by the amount of land designated for the production of the given food crop to obtain the total production in tonnes. Total production is multiplied by the respective energy densities per food staple to obtain the number of calories produced. The calories produced are summed across all food crops to obtain the total calories grown. The total calories grown is returned as an output for use in other sub-models as seen in **Figure 4.12**.

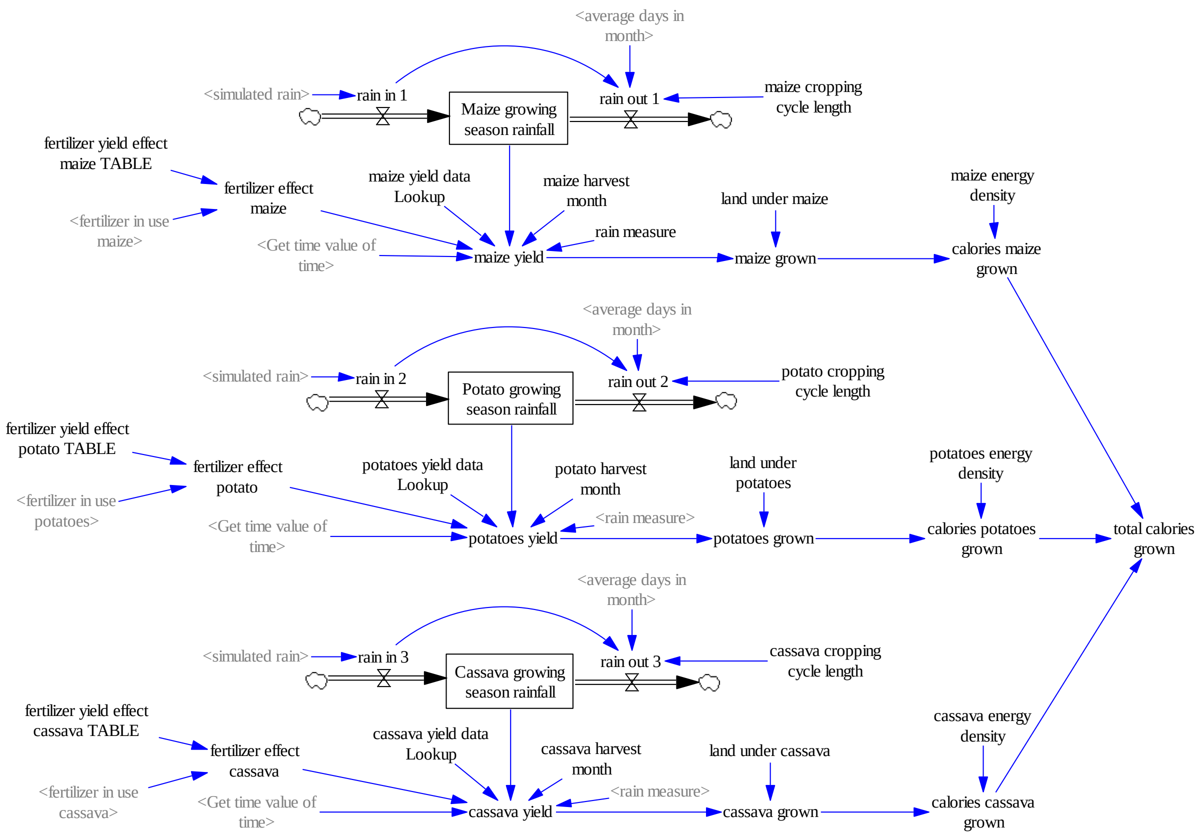

Figure 4.12: *Food Production Sub-Model*

4.3.3.3 Industrial cropping

The growth and production of the two ICs under examination are modelled in this sub-model. The production systems are considerably more complex than that of the food crops, however, the three major drivers remain the same. Again, both rainfall and the amount of land designated for the production of each crop are the exogenous drivers. Inputs remain the endogenous driver. For the modelling of sugarcane, the scope of inputs is extended to include irrigation. Some smallholder farmer plots are grouped into trusts, these are managed by associations. Of these trust operated plots, 25% have, or once had, irrigation infrastructure. To model this sub-system, the model allows for access to irrigation to be switched on or off, affecting the inputs and cost structure appropriately. Rainfall during the growing season of tobacco and sugarcane operate as two of the stocks.

Rate in: $$RI(t)_i = SR(t) \tag{4.5}$$

Stock: $$GSR(t)_i = GSR(t-1)_i + \int RI(t)_i - RO(t)_i \, dt \tag{4.6}$$

Rate out: $$RO(t)_i = DELAY\ FIXED(RI(t)_i, CC_i, 0) \tag{4.7}$$

Where, RI = rainfall in, SR = simulated rain, GSR = growing season rainfall, RO = rainfall out, CC = cropping cycle, i = {tobacco, sugarcane}.

Where irrigation is an option, the irrigation required is calculated as the difference between the optimal water requirement and the simulated rainfall for a location. The irrigation applied is a product of the required irrigation and that which the farmer can afford. The third stock monitors to what extent the smallholder farmer could afford to irrigate throughout the season.

Rate in: $$II(t) = PIP(t) \tag{4.8}$$

Stock: $$TIA(t) = TIA(t-1) + \int II(t) - IO(t) \, dt \tag{4.9}$$

Rate out: $$IO(t) = FIXED\ DELAY(II(t), CC_s, 0) \tag{4.10}$$

Where, II = irrigation in, PIP = percent irrigation afforded, TIA = total irrigation afforded, IO = irrigation out, CC_s *= cropping cycle sugarcane.*

Water availability is used in conjunction with the purchased inputs to determine the seasonal yield for both sugarcane and tobacco. The yield is multiplied by the land given to tobacco and sugarcane to determine production in tonnes. It is at this point that similarity between the tobacco and sugar sector ends. Produced cane is cut, loaded and delivered to the mill for further processing. The farmer is paid by the milling company (Illovo). Two different cost structures are modelled. The use of a cost structure is determined by whether the smallholder farmer is registered to the DCGT or to other associations. Management companies are strongly linked to associations. Those registered to the DCGT traditionally use the DCGL for farm management services. The DCGL charges more for services rendered to the farmer than the management companies used by other associations. The difference in cost charged to the farmer is reflected in the model.

The sugarcane price per tonne of cane is used to calculate the farmer's gross earnings. This equates to 60% of the total divisible proceeds from the sale of both sugar and molasses. The other 40% is retained by the Illovo as a milling charge (Corporate Citizenship, 2014). The costs for services rendered by the management companies and the tax paid to the Malawi Revenue Authority (MRA) is deducted from the earnings (CISANET, 2013). The cost of haulage is born by the farmer and is calculated per tonne cane shipped. The haulage cost is also deducted from the farmer's earnings. The farmer's net earnings are reflected in the model variable 'cane income' which is returned for use in other sub-models. Stock, rate and variable dependencies for sugarcane can be seen in **Figure 4.13**.

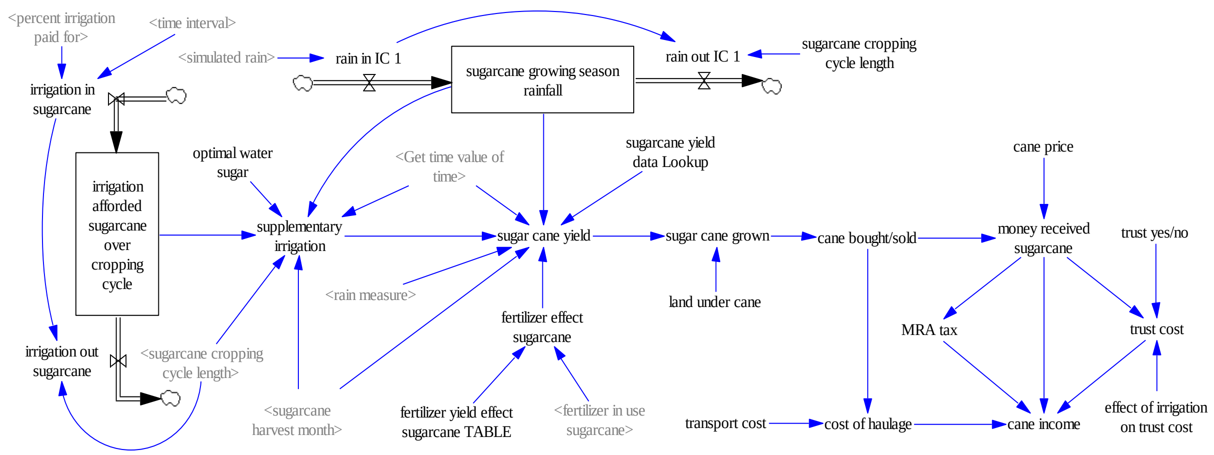

Figure 4.13: *Sugarcane Production Model*

Tobacco earnings are dependent on the price of tobacco and the costs incurred by the farmer. Like sugarcane, there are two different tobacco cost structures. The cost structure exercised is dependent on whether the farmer is an independent or contracted (IPS) farmer. IPS farmers have increased access to inputs through loans offered by the leaf companies. In some cases, receiving inputs as a loan is compulsory. Loan packages include various other items not necessary for the cultivation of tobacco, this includes maize seed and inputs for the growing of maize and seedlings to combat deforestation (Drope *et al.*, 2016). The costs of these items are incurred by the farmer regardless of a farmer's apparent want for such items. The items included in the loan packages are slightly more expensive than the cost of the items on the open market. Although it is noted that input prices on the open market or subject to higher price variability owing to occasional fertilizer subsidies. The difference in potential input and loan repayment costs are incorporated into the model and the farmer's net earnings are returned in the variable 'money received tobacco'.

4.3.3.4 Inputs

The input sub-model simulates input requirements and purchases. Irrigation and fertilizer requirements are considered inputs. This sub-model determines the required amounts of fertilizer for each crop and the required cost of the inputs in Malawian Kwacha (MWK) per hectare. The amount of land designated to each crop is the exogenous driver and is multiplied by the fertilizer cost per hectare to obtain the total required cost of fertilizer.

When a smallholder farmer does not have access to credit the model compares the farmer's available cash balance to the cost of the required inputs. When the farmer has sufficient cash, all inputs are purchased. If the farmer has no available cash reserves, no inputs are purchased. If the farmer can partially cover the cost of the required inputs, then only that which he can afford is purchased. Five stocks are declared in this sub-model. The stocks track the amount fertilizer purchased, as fertilizer in (FI), and fertilizer used (FU) as a percentage of the optimal fertilizer usage. The rate out, fertilizer out (FO), ensures fertilizer that is utilized by the crop exits the system.

Rate in: $$FI(t)_i = PIA(t)_i \qquad (4.11)$$

Rate out: $$FO(t)_i = FIXED\ DELAY(FI(t)_i, CC, 0) \qquad (4.12)$$

Stock: $$FU(t)_i = FU(t-1)_i + \int FI(t)_i - FO(t)_i\, dt \qquad (4.13)$$

Where, FI = fertilizer in, PIA = percentage inputs afforded, FO = fertilizer out, CC_i *= cropping cycle, FU = fertilizer used, i = {maize, potato, cassava, tobacco, sugarcane}*

Sugarcane and tobacco farmers that have credit access, the dynamics are somewhat different. To ensure that a loan payment is received in time for the purchase of inputs, the model checks for loan eligibility and the required sum of the loan in advance; except in the case where the loan is received in the form of inputs. Where a loan is compulsory, as is in the case of certain IPS contracts, a loan is triggered automatically regardless of available cash balances and the cost of inputs. The tobacco fertilizer model, which forms part of the input sub-model, is provided in **Figure 4.14** is provided as an example in which the layout, structure, and variables used in the calculation of the stocks and rates described in equations **(4.11), (4.12)** and **(4.13).**

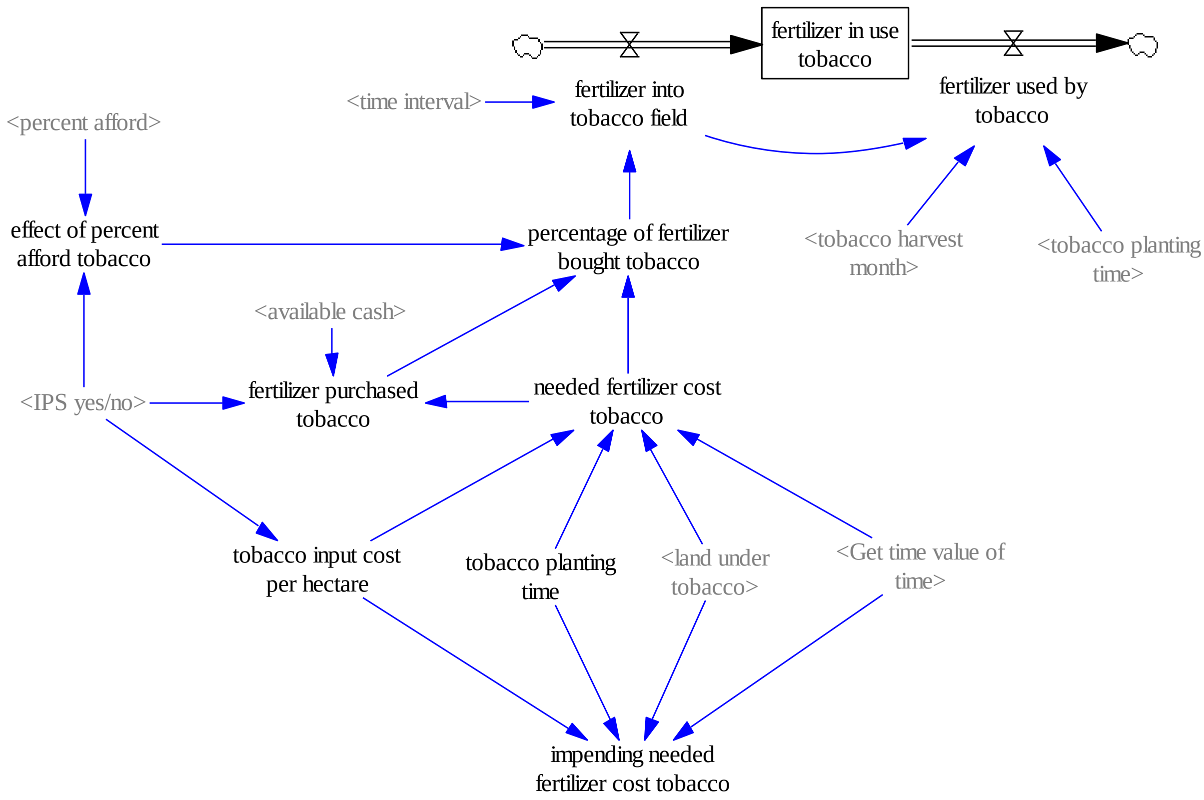

Figure 4.14: *Tobacco Fertilizer Model*

The inputs sub-model also calculates the irrigation costs. Where irrigation is managed by the DCGL or other management companies the direct cost to the farmer is waived and the fees for services rendered to the farmer are increased accordingly. The cost of irrigation reflects an initial capital investment cost in addition to maintenance costs.

4.3.3.5 Loans

Access to credit is modelled in this sub-model. Credit is only available to farmers engaged in either sugarcane or tobacco production. In both cases, the expected cost of inputs is returned from the 'inputs' sub-model. This value is compared to the available cash to determine the necessity of a loan. If a loan is required, the model checks for eligibility. This requires a farmer to be engaged in sugarcane production or to be an IPS contract farmer. It is important to remember that sugarcane farmers making use of the services of management companies will not require a loan to purchase inputs. Upon the successful application, the loan sum is received and a repayment, plus interest, triggered for a later date. In most cases, the value of the loan plus interest is deducted from the farmer's payment and a separate payment need not be made.

The model makes use of switches to allow for compulsory loans to be turned on or off for both tobacco and sugar farming. No stocks and accompanying rates are declared in this sub-model.

4.3.3.6 The farmer

The 'farmer' sub-model is where household decisions are made. The two primary decisions concern the buying and selling of food. There are three stocks declared in this sub-model. The first stock declared is that of 'food on table' (FOT). FOT is a caloric measure of the amount of food available for household consumption. FOT is affected by four rates. Food is added to the FOT stock through the 'household food supply' (HFS) rate. HFS is the sum of the food grown or bought for any given month. Food does not keep forever, and losses are experienced in food processing, handling, and storage. To this end 'post-harvest losses' (PHL) affects food stocks as the second rate.

Food sales (FS) is the third rate. Only excess food can be sold, and this is governed by the 'caloric sale threshold' (CST). The CST determines which crops are being cultivated and calculates the remaining time until another IC or food crop harvest.

The household's total energy requirements until the subsequent harvest are calculated as the CST. The effect of expected post-harvest losses is incorporated in this calculation. The difference in the food stocks and the CST are available to be sold. When food stocks are lower than the threshold, food will not be sold.

Household consumption (HC) is the final rate. HC is a function of the household size, DER, and the available food (FOT). The household size is set to 4.6, the average household size in Malawi (NSO, 2012). The DER is set to 2400kcal per person per day (FAO, 2008). While food is available, household members strive to consume 2400 kcal/day. When insufficient food is available to meet minimum household consumption needs, and food cannot be bought, household members will go hungry; eating the remaining food until stocks are fully depleted. The average household member's caloric consumption is tracked as this study's primary food security indicator.

Rate in: $$HFS(t) = CB(t) + CG(t) \qquad (4.14)$$

Rate out: $$FS(t) = CS(t) \qquad (4.15)$$

Rate out: $$PHL(t) = MAX(CL(t) \times FOT(t), 0) \qquad (4.16)$$

Rate out: $$HC(t) = MAX\left[0, MIN\left(TRC(t0, FOT(t))\right)\right] \qquad (4.17)$$

Stock: $$FOT(t) = FOT(t-1) + \int HFS(t) - FS(t) - PHL(t) - HC(t)\, dt \qquad (4.18)$$

Where, HFS = household food supply, CB = calories bought, CG = calories grown, FS = food sales, CS = calories sold, PHL = post-harvest losses, CL = combined losses, FOT = food on table, HC = household consumption.

The sale and purchase of food trigger a cash transaction. The household's wealth is stored in the 'available cash' (AC) stock. The AC stock is affected by four rates. 'Income' (I) is the sum of sugarcane, tobacco, other off-farm income, and cash obtained through food sales. Cash is also received when a loan is paid out. The loan (L) rate reflects loans obtained through sugar or tobacco cultivation when returned from the loans sub-model. 'Expenses' (E) flow out from the stock. E is the sum of the minimum non-food purchases (NSO, 2012), total input expenses, and the cost of purchased food. 'Debt repaid' also draws from the available cash. Debt repayments are incurred by outstanding loans. In the case of insufficient funds, inputs will not be purchased, debts will not be repaid, and food cannot be purchased. An assumption is made that when some cash remains but not all costs can be met, the purchase of food takes priority.

Rate in: $$I(t) = CI(t) + FSC(t) + OI(t) + TI(t) \tag{4.19}$$

Rate in: $$L(t) = LS(t) \times (1 - LI_s(t)) + LT(t) \times (1 - IPS) \tag{4.20}$$

Rate out: $$E(t) = MAX(TE(t) \times PA(t) + FE(t), 0) \tag{4.21}$$

Rate out: $$DR(t) = RDR(t) \times PA(t) \tag{4.22}$$

Stock: $$AC(t) = AC(t-1) + \int I(t) + L(t) - E(t) - DR(t)\, dt \tag{4.23}$$

Where, I = total income, CI = cane income, FSC = food sales cash, OI = other income, TI = tobacco income, L = loan, LS = loan sugar, LI_s = loan as inputs sugar, LT = loan tobacco, IPS = integrated production system, E = expenses, TE = total expenses, PA = percent afford, FE = food expenditure, DR = debt repaid, TDR = required debt repayment, AC = available cash.

A final stock, remaining debt (RD), keeps track of unpaid debt. The rate 'debt not paid' is calculated as the difference between the required debt repayments and that which is actually repaid by the farmer. The farmer's net worth is the difference between total assets, the available cash, and total liabilities, remaining debt.

Rate in: $$DNP(t) = RDR(t) - DR(t) \tag{4.24}$$

Stock: $$RD(t) = RD(t-1) + \int RD(t)\, dt \tag{4.25}$$

Where, DNP = debt not paid, RDR = required debt repayment, DR = debt repaid, RD = remaining debt.

The structure, layout, and linked variables used in the calculation of the stocks and rates of the farmer sub-model can be seen in **Figure 4.15**.

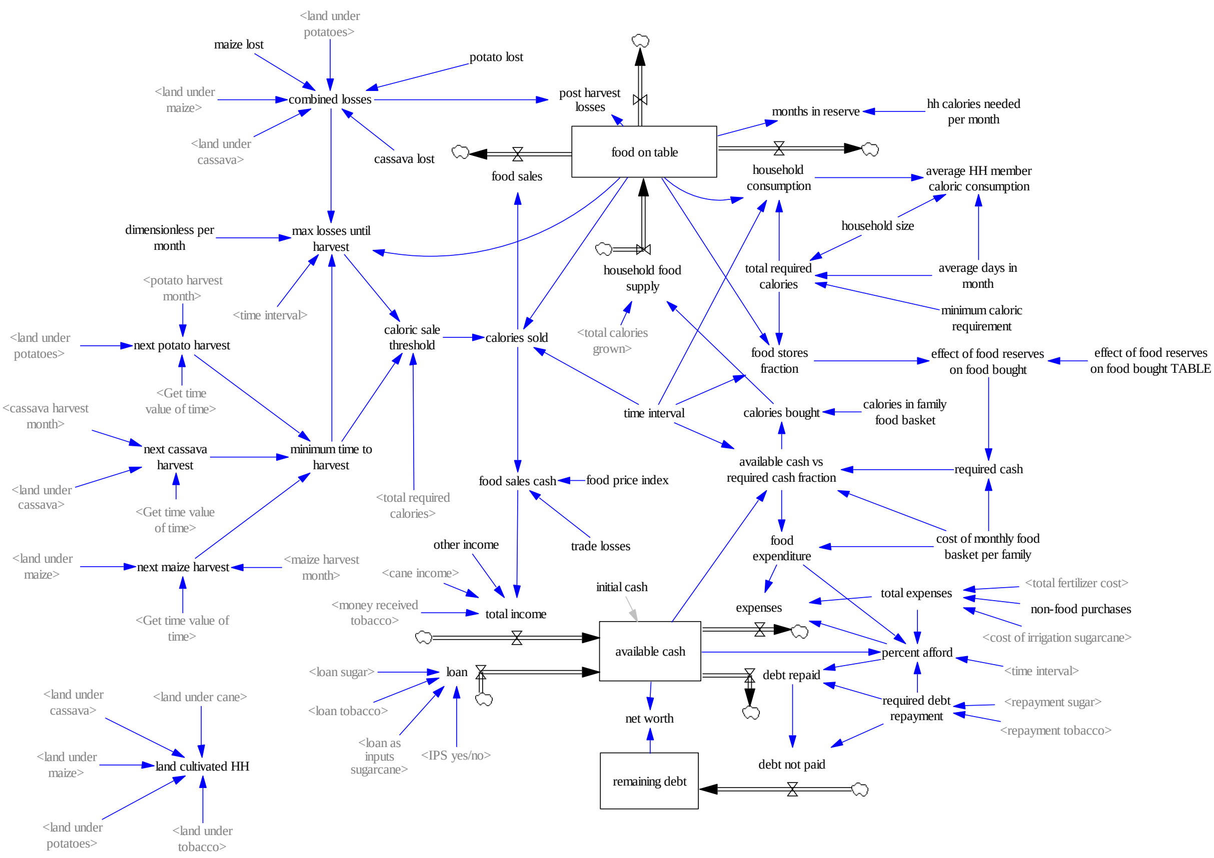

Figure 4.15: *The Farmer Sub-Model*

4.4 Model testing and validation

Model validation is an important step in the SD methodological process. There is no single test that validates an SD model, rather, confidence in an SD model accumulates gradually as the model passes more tests and as increasing agreement is established between the model and empirical reality (Forrester & Senge, 1980). Steps for model validation are outlined in **Figure 4.16**, the steps followed have been adapted from those recommended by Forrester and Senge (1980) and Maani and Cavana (2007).

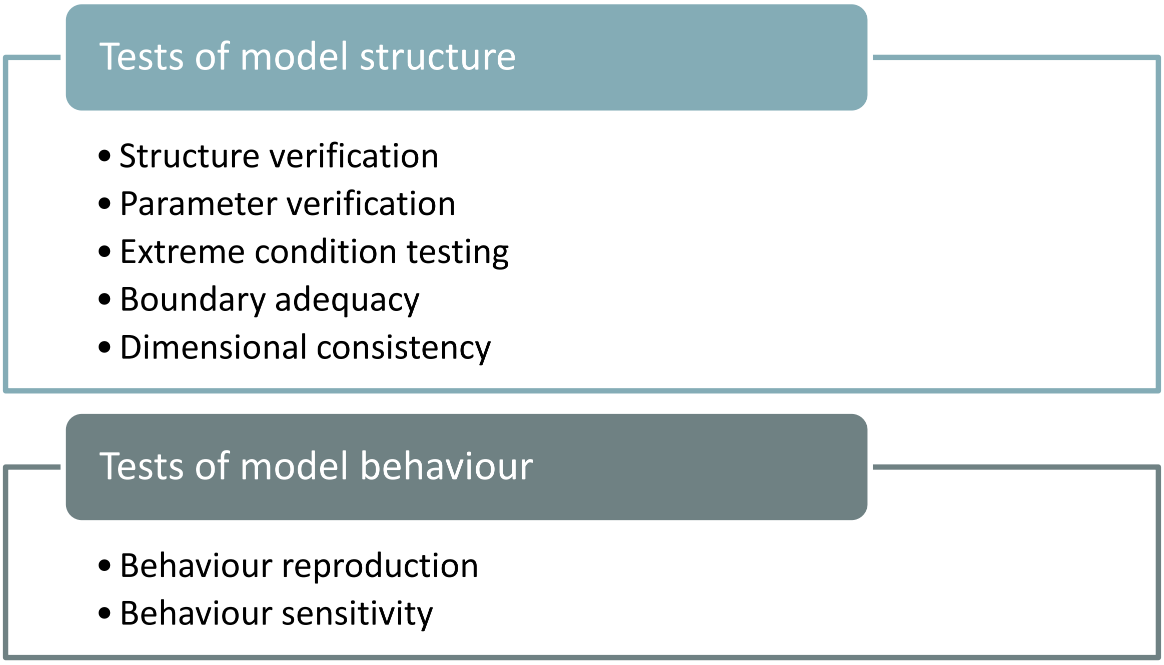

***Figure 4.16**: Steps of Model Validation*

4.4.1 Tests of model structure

4.4.1.1 Structure verification

Verifying a model's structure means comparing the structure of the model to that of the real system which it aims to represent. A model that does not contradict any knowledge of the structure of the real system passes the structure verification test. In most cases, the structure verification test is first conducted based on the modeller's personal knowledge and is then extended to include criticisms by those who have direct knowledge and experience of the real system. This is done with regard to decision making and organisational relationships (Forrester & Senge, 1980).

Structure verification was undertaken in three distinct steps. Firstly, after the construction of the conceptual model, the modeller travelled to the location of analysis to verify the model's assumed relationships and investigate for additional uncaptured relationships within the system. This was the modeller's first visit to the location of analysis. This involved participation in stakeholder discussions and the observation of mechanisms at work. The conceptual model was then updated based on the stakeholder inputs and that which was observed in the real system.

The construction of the simulation model was based on the last iteration of the conceptual model. With the original simulation model largely completed, the modeller returned to the location of analysis. The first half of the visit was aimed at data patching and corroboration, discussed in the parameter verification section. The second half of the visit was used for checking the model's structure and operation and whether it imitated the that which was observed in the real system.

Stakeholders at all levels were engaged to determine structural validity. To this end, the modeller met with employees of various tobacco leaf companies, employees of Illovo, employees of companies subcontracted by Illovo, ex-employees of the industry (to obtain insight into conflicting information), and smallholder farmers. Based on stakeholder inputs the model was updated accordingly.

The third step of structure verification was through the use of respected academics. This took the form of two distinct engagements. For the first engagement, the modeller travelled to the United Nations University (UNU) in Tokyo, Japan, to present the model structure and modus operandi to academics of the FICESSA project in 2016. For the second engagement, the modeller travelled to the Royal Botanic Gardens, Kew in London, U.K to present another iteration of the simulated model. Criticisms were recorded, reviewed, and the model structure changed to provide a better representation of the real system after each engagement. Those academics and scientists consulted for input into the model included Prof Alexandros Gasparatos (University of Tokyo), Dr. Kathy J. Willis (Director of Science, Royal Botanic Gardens Kew), Dr. Steve Wiggins (ODI), Prof Marc Macias-Fauria (University of Oxford), Dr. Thomas Etherington (Royal Botanic Gardens Kew), Dr. Marcin Jarzebski (University of Tokyo), and Dr. Graham von Maltitz (CSIR).

4.4.1.2 Parameter verification

While the structure of the model is compared to the available knowledge of a system, model parameters (model constants) can be verified by observations in real life (Forrester & Senge, 1980). To pass the test, parameters must correspond conceptually and numerically.

Parameters or constants are needed to populate the model with data. Model population only commences with the construction of the simulated model. The data used in the model comes from a variety of different sources. The initial data were obtained from the literature. The first step of parameter verification was to ensure that data obtained through the literature was supported in other literature. Where the information needed to populate model parameters was not available in the literature, or where data or information available in the literature was contradictory or inconclusive, then data were obtained in the field. The collection of field data and the use of this data for existing parameter verification was step two of the parameter verification procedure.

The two location visits described in the structure verification section were used as opportunities to obtain missing data (data patching) and verify data obtained through the literature. Data not available in the literature pertaining to the location of analysis or unobtainable on location was obtained through the consultation of various experts in the field. To this end, the engagements in Tokyo and London respectively were used to consult experts knowledgeable in the system of study.

The engagements were also used as the final means of parameter verification for all data obtained through the literature and on location.

4.4.1.3 Extreme condition testing

Structure in an SD model should permit extreme combinations of levels in the system being represented (Forrester & Senge, 1980). The extreme conditions test requires the examination of each rate equation in the model and all the auxiliary equations on which the rate depends. For each variable, the modeller must consider the implications of extremely high, extremely low, and of zero values.

Forrester and Senge (1980) argue that the extreme conditions test is effective for two reasons. It is a vigorous tool for determining flaws in the model structure because many model relationships might seem plausible until considered under extreme conditions, this is the first reason. The second is that extreme parameter testing increases the usefulness of a model for the analysis of policies or scenarios beyond the typical region of historical observation. A model that can behave plausibly for a wide range of conditions is a model that better represents the real system.

A review of the model's rates and auxiliary variables revealed that the rainfall sub-model and crop sub-models were not set up to handle extreme rainfall, that which falls outside of the expected rainfall based on historical observed data. The model was altered accordingly to incorporate a plausible response to extreme rainfall should it occur. This was revealed during extreme maxima tests.

It was also noted that when calculating the percentage of inputs bought by the farmer, calculated as the amount of inputs the farmer could afford relative to the cost of required inputs, if the cost of required inputs assumed a value of zero then that auxiliary variable would become undefined. While not affecting the running of the model, the value of what was purchased versus what was needed did not accurately reflect that of the real system. The model was adjusted to ensure the denominators in all calculations were strictly non-zero. This was revealed during the testing of auxiliary variables with zero values.

4.4.1.4 Boundary adequacy

Structure verification tests whether the structure in the model is apparent and representative of that in the real system, boundary adequacy tests whether the model includes all relevant structure in the real system and whether the level of model aggregation is appropriate. Boundary adequacy and structure verification are closely related. Any additions to the model in the structural verification procedure are a direct result of the model failing previous boundary adequacy tests. Any additions added to the model must then also undergo structural verification tests. The process is iterative and is was conducted simultaneously with that of the structural verification step.

4.4.1.5 Dimensional consistency

Forrester and Senge (1980) describe this test as 'mundane but revealing.' The dimensional consistency test forms a vital part of ensuring simulation construction is done in a logical manner. The software package selected for this simulation, Vensim, contains a built-in units checker. If the all the input units used in the formulation of an equation do not match the selected units of the output a units exception error is thrown. This model receives the message 'units are OK' when the check is performed which shows dimensional consistency.

4.4.2 Tests of model behaviour

4.4.2.1 Behaviour reproduction

Forrester and Senge's (1980) family of behaviour reproduction tests examine to what extent the simulated model's behaviour reproduces that which is observed in the real system. Four behaviour reproduction tests are identified. The reference modes constructed earlier convey the patterns or trends of the modeller's expected simulated outputs based on the observed system. These provide a helpful tool in the comparison of expected and actual model outputs and is useful for model validation.

Frequency-generation test

The frequency generation test assesses a model's ability to reproduce periodicities of fluctuation and the phase relationships between variables. Periodicities observed in the real system must be reliably reproduced in the simulated outputs. Rainfall in Malawi is highly seasonal and rainfall that reflects the observed historical data must be reproduced by the model to pass this test. A comparison of the reference mode to the rainfall produced by the model can be seen in **Figure 4.17**. The model accurately models the expected periodicity.

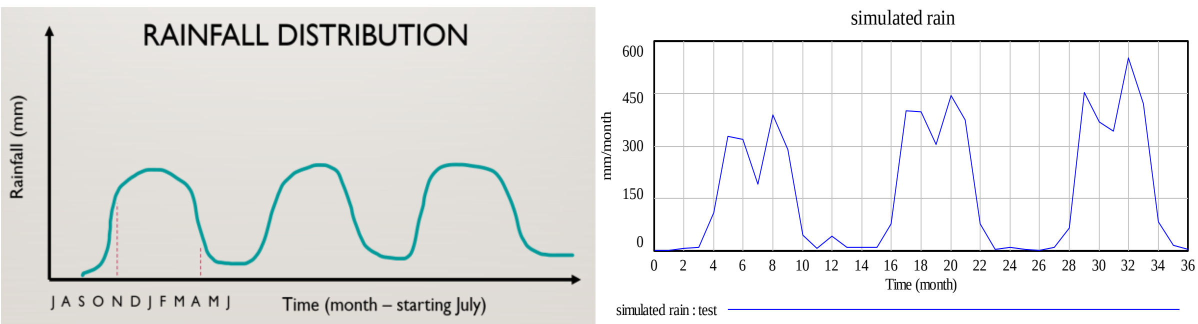

***Figure 4.17**: Model Behaviour Test 1*

Symptom-generation test

The symptom-generation test examines whether the simulated model can recreate the symptoms of difficulty that motivated the construction of the model (Forrester & Senge, 1980). SD models are created to explain how an undesirable situation, as defined in the problem statement, arises. Changes to the system can be tried and tested in the model to alleviate the situation. Forrester and Senge (1980) argue that unless one can recreate the problem symptoms as a function of the policies and the model structure the problem causes cannot be addressed.

The problem symptom is a lack of food security for Malawian smallholder farmers. Hunger is observed to be most prevalent just before the new season's harvest during the months of December, January, and early February when food stocks have been exhausted. In the months just prior to this, a household is expected to begin rationing food to ensure the household members have access to at least some food for as long as possible. This is indicated in **Figure 4.18** by a gradual decline in food consumption and not an immediate drop to zero.

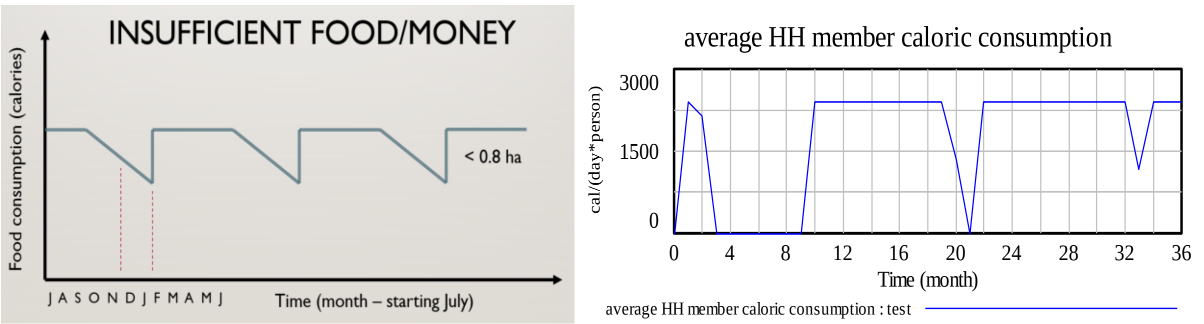

Figure 4.18: *Model Behaviour Test 2*

Insufficient consumption, the problem symptom, is adequately recreated by the simulated model as shown in **Figure 4.18**. The model's inability to simulate food rationing is a limitation. However, the objective of the model is to indicate levels of food insecurity under several scenarios. This is indicated by any deviation from a consumption of 2400 kcal per day. Whether consumption approaches zero gradually or suddenly is trivial as any departure from a flat line at 2400 kcal indicate insufficient levels of food security.

Multiple-mode test

The multiple-mode test demonstrates whether a model can generate more than one mode of observed behaviour. With the problem-symptom being sufficiently reproduced the model is known to produce at least one mode of observed behaviour. Parameter changes to the system that are known to induce a particular secondary mode based on observations in the real system, must lead to a similar change and system behaviour in the simulated model. Parameter changes, even if not optimal, likely, or possible, but that are known to produce high levels of food security are made to the simulated system to determine if the model structure allows for the generation of more than one mode and can reproduce the observed system behaviour. The simulated outcome generates a second mode and passes the multiple mode test as demonstrated in **Figure 4.19**.

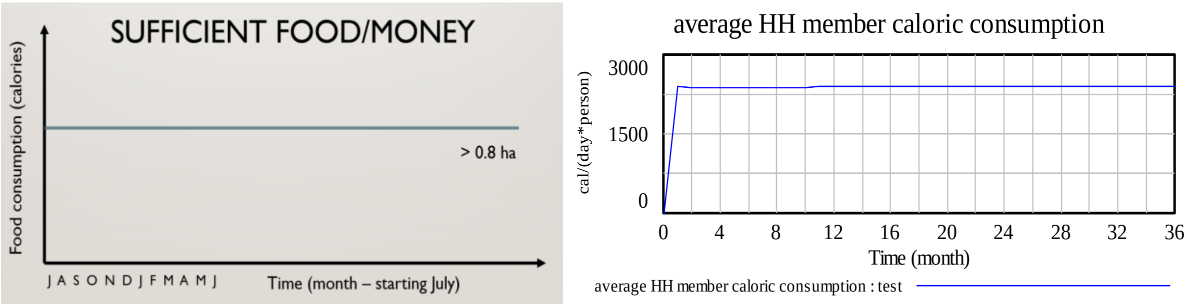

Figure 4.19: *Model Behaviour Test 3*

Behaviour characteristic test

The remaining reference mode will is used as a basis for comparison in the behaviour-characteristic test. The behaviour-characteristic test is a miscellaneous category for any other behaviour-reproduction tests (Forrester & Senge, 1980). In this test, a model is expected to show a pattern of circumstance or trend observed in the real system in the simulated system. In **Figure 4.20**, the expected cash reserves of a smallholder farmer that is achieving food security over time is shown. The hypothesis of wealth leading to more wealth is captured. The simulated cash balance is shown is **Figure 4.20** and adequately reproduces the expected trend.

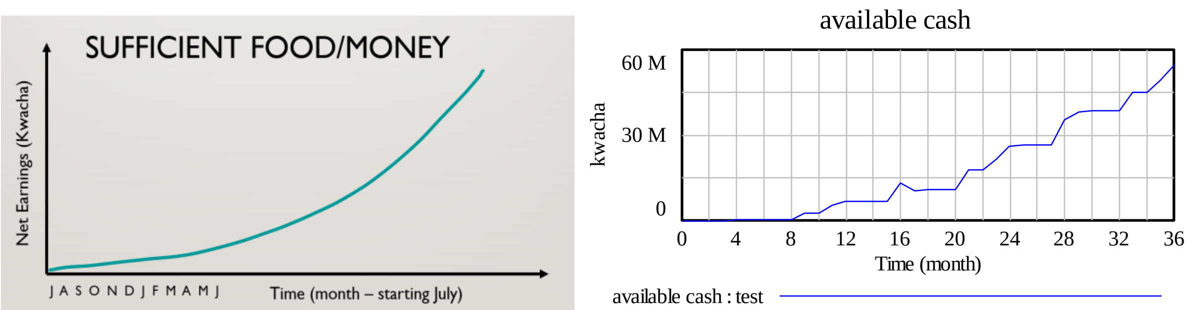

Figure 4.20*: Model Behaviour Test 4*

4.4.2.2 Behaviour-sensitivity test

Behaviour-sensitivity tests aim to determine the model's sensitivity to parameter values (constants). It must be stressed that sensitivity within a model is not necessarily a good or a bad thing. All models will be sensitive to certain parameters and not to others, in fact, oftentimes the ability to determine what parameters the system is sensitive to is the reason for model construction.

Sensitivity analysis is important for three reasons. Firstly, it is a useful tool for detecting model anomalies. A Monte Carlo simulation might reveal if there exist ranges of parameter values to which the model is overly sensitive too. Secondly, where sensitivity analysis reveals a model to be sensitive to a particular parameter and the value used for that parameter is the result of statistical analysis (aggregation etc.), then the sensitivity analysis has helped the modeller identify an area requiring extra effort to ensure confidence in the model. Thirdly, where better data is not available the sensitivity analysis can be used as a tool for interpreting model results. A Monte Carlo simulation helps provide the modeller with an upper and lower boundary, forming an envelope in which the result will lie, partitioned into levels of confidence. A Monte Carlo simulation was run for the model on a variety of parameters, two of which are shown here.

The first simulation aimed to determine the sensitivity of food security and available cash to the cost of the fees for services rendered charged by the sugarcane management companies to the smallholder farmers. A fee of 8% was used as the lower boundary and a fee of 22.5% was used as the upper boundary. The effect of variations in the cost of services rendered on the available cash can be seen in **Figure 4.21** and its effect on household food consumption in **Figure 4.22**.

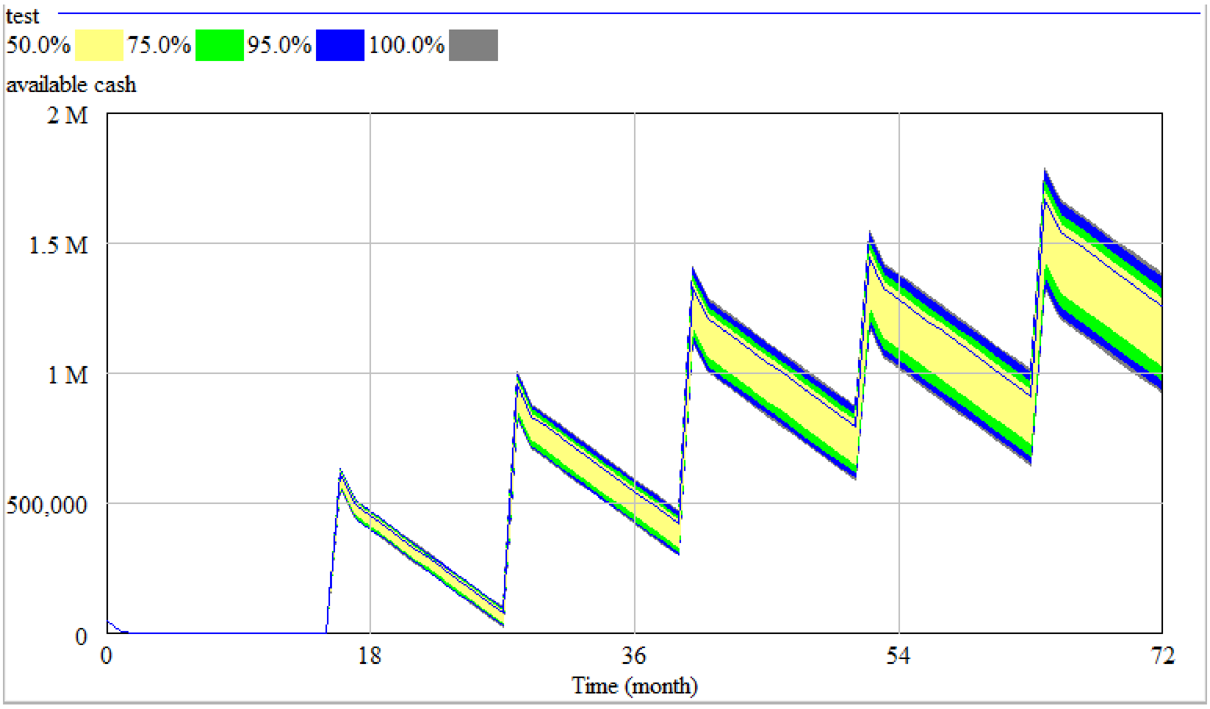

Figure 4.21: *Sensitivity of Available Cash to Sugarcane Fee Deductions*

Both the state of food security and the accumulated wealth are not particularly sensitive to the percentage of proceeds deducted from the farmers' earnings by the management companies. Discussions with smallholder development consultant Kate Mathias (Mathias, 2017) revealed that smallholder success is likely not determined by the distribution of divisible proceeds. This verifies the results of this sensitivity analysis.

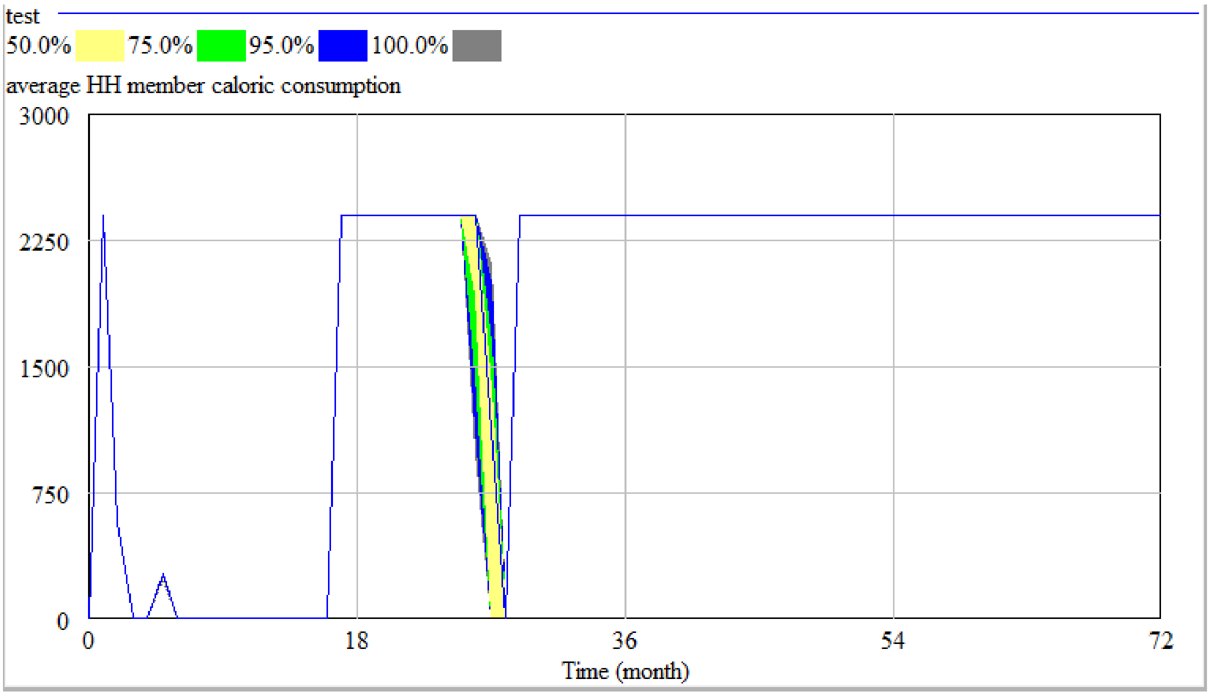

Figure 4.22: *Sensitivity of Household Consumption to Sugarcane Fee Deductions*

The second Monte Carlo simulation aimed to determine the effects of the tobacco price on available cash and household consumption respectively. A lower boundary of $0.9 per kg and an upper boundary of $2.37 per kg was used in the formulation of this Monte Carlo simulation. This captures the highest and lowest observed price of Burley tobacco in the last 20 years. Both the household's accumulated wealth (**Figure 4.23**) and food security (**Figure 4.24**) are highly sensitive to the price of Burley tobacco. Discussions with stakeholders and the prevailing literature highlighted the farmer's vulnerability owing to tobacco price fluctuations and verifies the results of the sensitivity analysis.

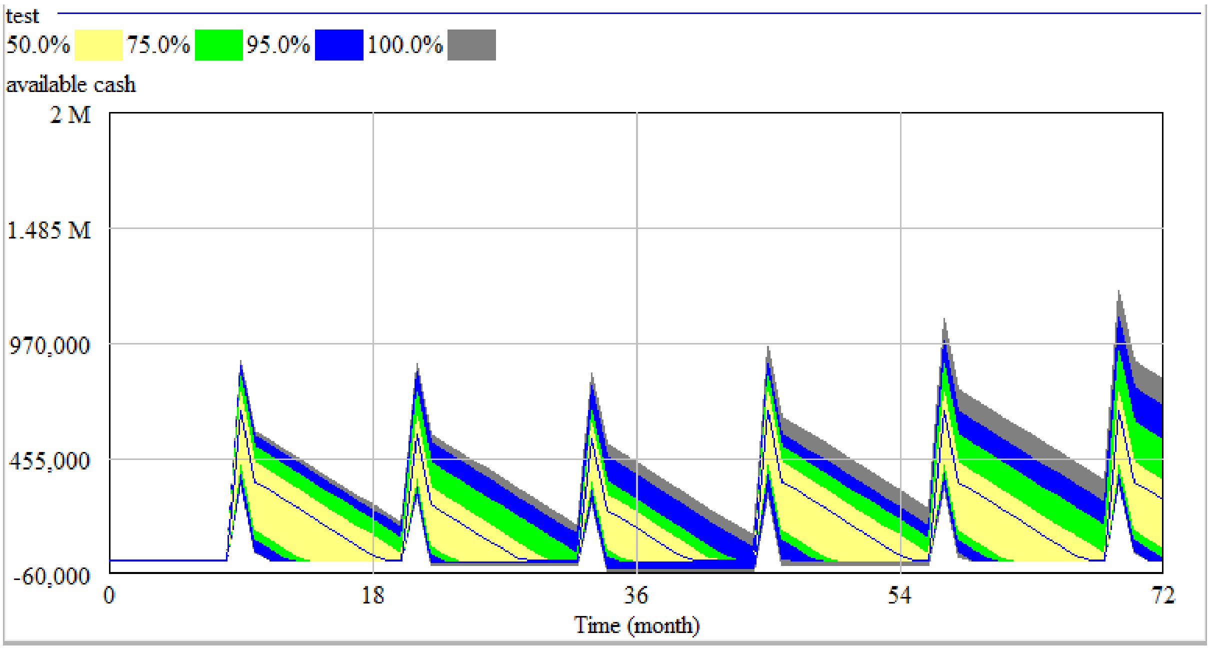

Figure 4.23: *Sensitivity of Available Cash to Tobacco Price*

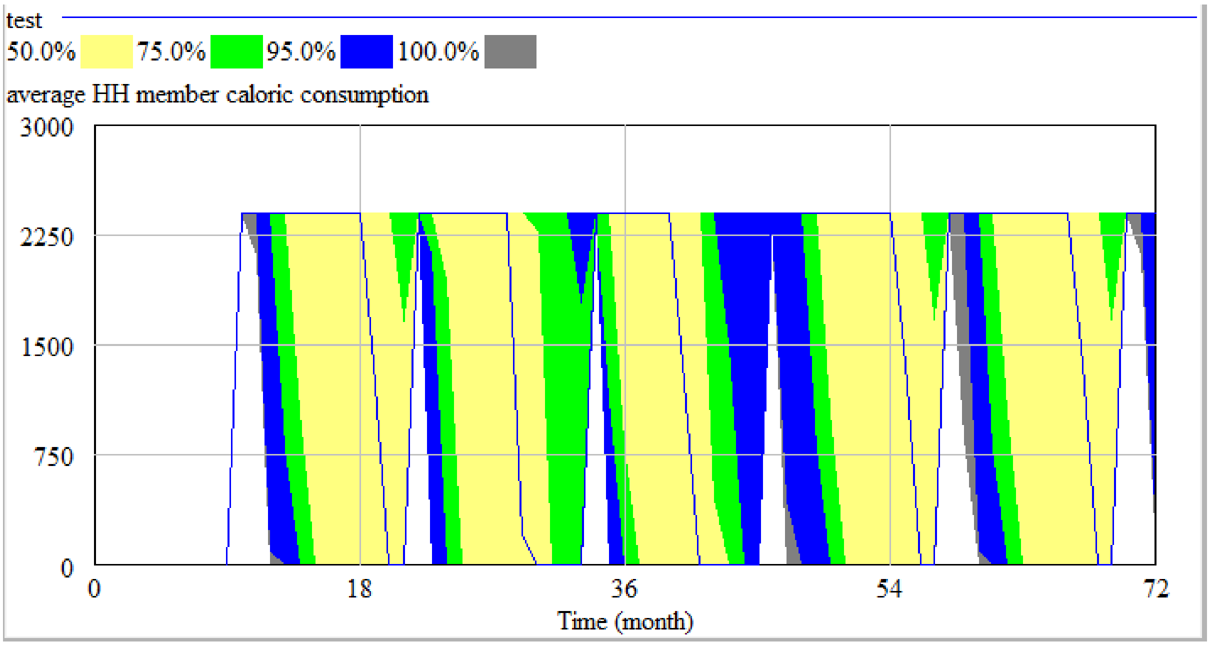

Figure 4.24: *Sensitivity of Household Consumption to Tobacco Price*

4.5 Scenario planning and modelling

Scenarios allow the modeller to subject the system to a variety of environmental conditions or to test how the system responds to different strategies and policies. A scenario is not a forecast (Maani & Cavana, 2007). Rather, it encourages thinking of situations outside of what the future is expected to look like and promotes the formulation of 'if…then' responses to a variety of possible situations.

The study aims to determine the effect of ICs on smallholder food security, where the focus is on the decisions available to the smallholder farmer. Distinguishing between external conditions, over which the smallholder farmer can exert no control, and areas where the smallholder farmer has influence and is therefore faced with a decision, allows for scenarios to be organised into environmental scenarios and strategic scenarios respectively.

4.5.1 Environmental Scenarios

Those scenarios that might arise over which the smallholder farmer has limited to no control are environmental scenarios. These factors include rainfall, access to land, starting capital, and the cost of inputs. Rainfall is clearly an environmental condition over which the farmer can exert no control. Malawi is a small country with a large population of smallholder farmers; land is at a premium. The most recent national integrated household survey (NSO, 2012) revealed that 80% of land ownership was reported as inherited, with almost 10% granted by local leaders (chiefs), while only 2.4% of land acquired was purchased. The land available to a smallholder farmer is most often a birthright and is considered an environmental condition in this study.

A smallholder farmer’s starting capital is also a birthright. This capital is the sum of resources available to the farmer and is represented in the model as a monetary value. These resources could take the form of the tools available to the farmer through family ownership, cuttings available to the farmer from family members, number of cattle owned, and personal savings etc. The total resource capital available to a farmer is a result of the farmer’s familial wealth or the relative affluence of the farmer’s village or immediate community. Thus, the value for ‘initial cash’ is an environmental condition. The cost of inputs is another factor over which the farmer has no control. The smallholder farmer has no control over whether the government decides to offer fertilizer subsidies or not for any given year. Input costs are therefore an environmental condition. In **Table 4.6** the four environmental conditions are further organised with values corresponding to three environmentally driven scenarios.

Table 4.6: *Environmental Scenarios*

Environmental conditions	Rain (mm)	Land (ha)	Capital (MWK)	Input subsidies
Worst case	Rainfall variability is captured within the model dynamics	0.4	0	No subsidy
Best case		1.4	high	Fertilizer subsidy
Most likely		0.77 ≈ 0.8	low	No subsidy

In **Table 4.6**, the values for the starting capital for each of the three cases is reported as 0, high, and low respectively. The 'initial cash' value is the amount of cash the farmer 'has' or is given at the beginning of the simulation. This was set as a slider within the model allowing for different values to be selected as required. There are three reasons for this. The first is that there is insufficient data as to what capital - resource, monetary, or otherwise – a farmer has access to. The second is that should there be data available as to what resources a farmer has access to, large assumptions need to be made to convert this 'resource value' to a single monetary value. The third reason is that the effect of this value on long-term food security is unclear. Small increments in value, or the passing of a tipping point, might have significant long-term impacts on food security. The ability of the model to run results for varying values of the model variable 'initial cash' is important if one is to capture these effects.

The values chosen for the amount of land available to farmers for each of the three scenarios above correspond to the average plot size values for the lowest, middle, and highest consumption quintiles reported by the Integrated Household Survey of Malawi (NSO, 2012). The value given to 'capital' for the most likely scenario was MWK 50 000 (roughly R1000 or $70), that which was found to be the average savings of Malawian farmers after two years in a study conducted by Flory (2016). Government subsidies on fertilizer were set to 70% of commercial market price (Sibande, Bailey & Davidova, 2017).

4.5.2 Strategic scenarios

Strategic scenarios are potential scenarios that might exist based on parameter values that the smallholder farmer can exercise control over. These are the decision variables. It is from the results of these scenarios that the best strategy or strategies can be determined. The first decision variable available to the smallholder farmer is that of land partitioning and crop choice. How much area should be given to each crop?

There are infinite ways in which a farmer's land can be partitioned between the five crops examined in this study. The first step is to allow for a pure comparison of crop performance. Monocropping with each of the three food crops and two ICs will be simulated by the model for each of the three environmental scenarios. The next step is to determine whether crops are complimentary; where a combination of crops might provide an increased state of food security that is better than either one achieves individually.

With infinite combinations of crop partitioning and pairing available some logical judgement must be made by the modeller in determining which scenarios might have a higher probability of yielding positive results. Combinations, seen in **Table 4.7**, were chosen such that cropping cycles, planting time, and harvesting time are sufficiently staggered. Staggered planting and harvesting times translate to staggered costs and earnings which is thought to impact food security. Five different strategies have been selected for trial. The first is a combination of food crops that have different cropping cycles. The next two strategies combine each of the two ICs paired with a food crop with a harvest time most different to that of the IC. The remaining two strategies are composites of Malawi's favoured staple (Maize), balanced with the typically drought-resistant cassava, and each of the available ICs in sequence.

Table 4.7: *Smallholder Strategies (percentage of area)*

Strategy	Maize (%)	Potato (%)	Cassava (%)	Sugarcane (%) + trust	Tobacco (%) + IPS
1	100	0	0	0	0
2	0	100	0	0	0
3	0	0	100	0	0
4	0	0	0	100	0
5	0	0	0	0	100
6	75	0	25	0	0
7	0	0	25	0	75
8	25	0	0	75	0
9	25	0	25	50	0
10	25	0	25	0	50

Chapter 5: Results and analysis

The results of the various scenarios and farming strategies, discussed in **section 4.5,** are presented and analysed in this chapter. First, the baseline scenario is presented. Results for three scenarios – a worst-case, a best-case, and a most likely scenario - are presented here for the area of Dwangwa, Nkhotakota District, Malawi. Results for the entirely different climatic region of Nchalo, Chikwawa District are used to validate findings and to help illustrate concepts and points where appropriate.

5.1 Baseline scenario

The baseline was chosen with the default cropping pattern for much of Malawi's arable land; maize monocropping. The baseline scenario was chosen as the most likely scenario outlined in **Table 4.6**. Households of 4.6 people, farming a plot of 0.8 ha, cannot maintain the minimum daily DER under this cropping pattern and scenario conditions. Periods of food shortages are evidenced in **Figure 5.1**. Under these conditions, there is no surplus food production available to be sold and thus earnings do not accumulate. A lack of accumulated earnings is reflected in **Figure 5.2**. The baseline uses rainfall conditions simulated for Dwangwa, Nkhotakota District.

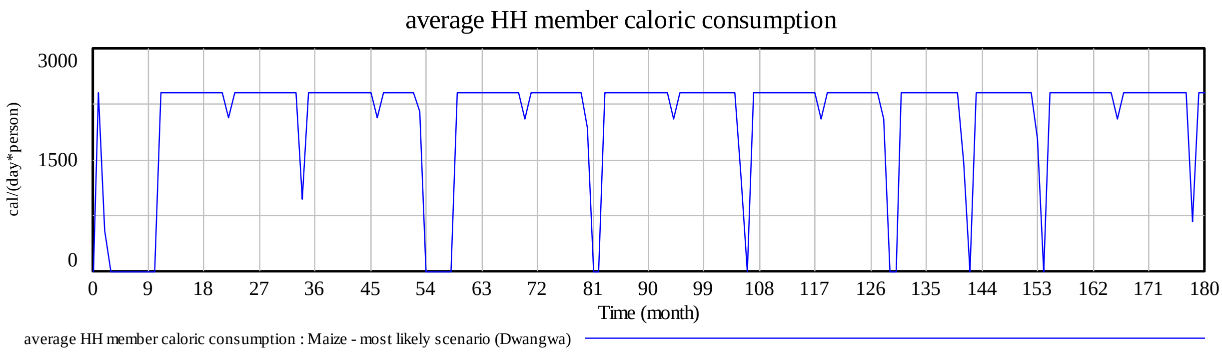

Figure 5.1: *Baseline consumption*

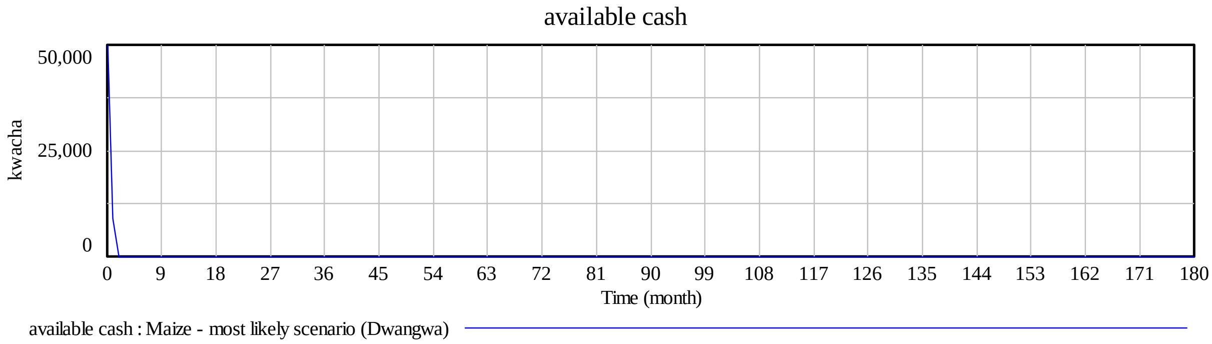

***Figure 5.2**: Baseline earnings*

5.2 Dwangwa

5.2.1 Worst-case scenario

For the worst-case scenario, plot size was set to 0.4 ha, starting capital was set to zero, and there was no subsidy in effect. Worst-case assumptions were made accordingly for both sugarcane and tobacco farming. Sugarcane farmers were assumed to be independent farmers, without access to credit or irrigation. Tobacco farmers were also assumed to independent farmers, therefore ineligible for IPS loans, without access to other credit facilities.

5.2.1.1 Monocropping

Considering strategies 1 – 5 outlined in **Table 4.7**, planting 0.4 ha of maize and potatoes did not ensure food security for the household of 4.6 people through any single year of the 15-year period. Farmers who planted sugarcane fared somewhat better, as can be seen in **Figure 5.3**, experiencing a number of food shortages but also able to meet at least partial food requirements through many of the traditional 'hunger-months'. The two best-performing crops for the Dwangwa area were cassava and tobacco. Tobacco farmers only saw one year in which food requirements of 2400 kcal were not met. Households that farmed cassava could maintain their daily DER throughout the 15-year period.

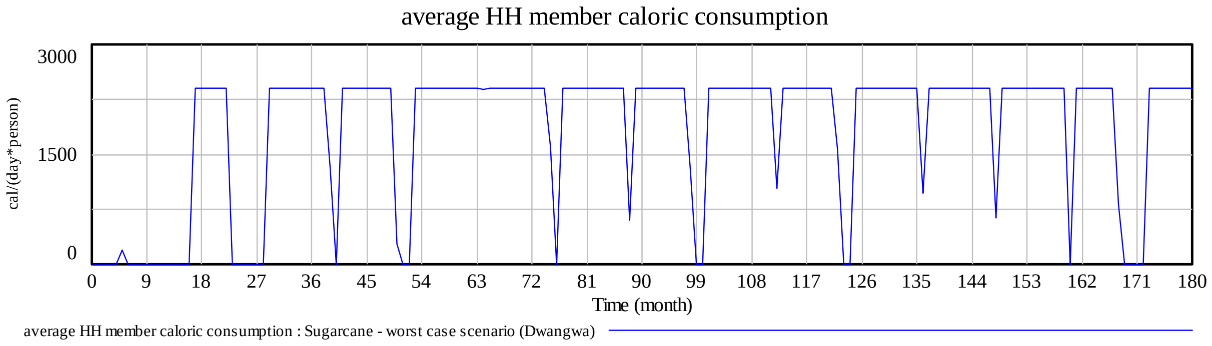

***Figure 5.3:** Household consumption per capita (Sugarcane)*

Only cassava and tobacco farmers saw any long-term wealth accumulation. Households that farmed cassava accumulated around MWK 2.4 million by the end of the 15-year period. This amounts to R48 000 (USD 3400) over 15 years or a meagre R3200 (USD 230) earnings per year.

5.2.1.2 Mixed-cropping

Of strategies 6 – 10 outlined in **Table 4.7**, farmers who cropped their 0.4 ha at 75% maize and 25% cassava (M75:C25) could not meet their daily DER. Households that adopted a cropping pattern of 75% sugarcane and 25% maize (S75:25M) fared significantly better, however, still experienced food shortages in 6 of the 15 years. The three cropping patterns of 50% sugarcane, 25% maize and 25% cassava (S50:M25:C25); 50% tobacco, 25% maize and 25% cassava (T50:M25:C25); and 75% tobacco and 25% cassava (T75:C25) provided returns that allowed for households to achieve the consumption goal of 2400 kcal per person per day.

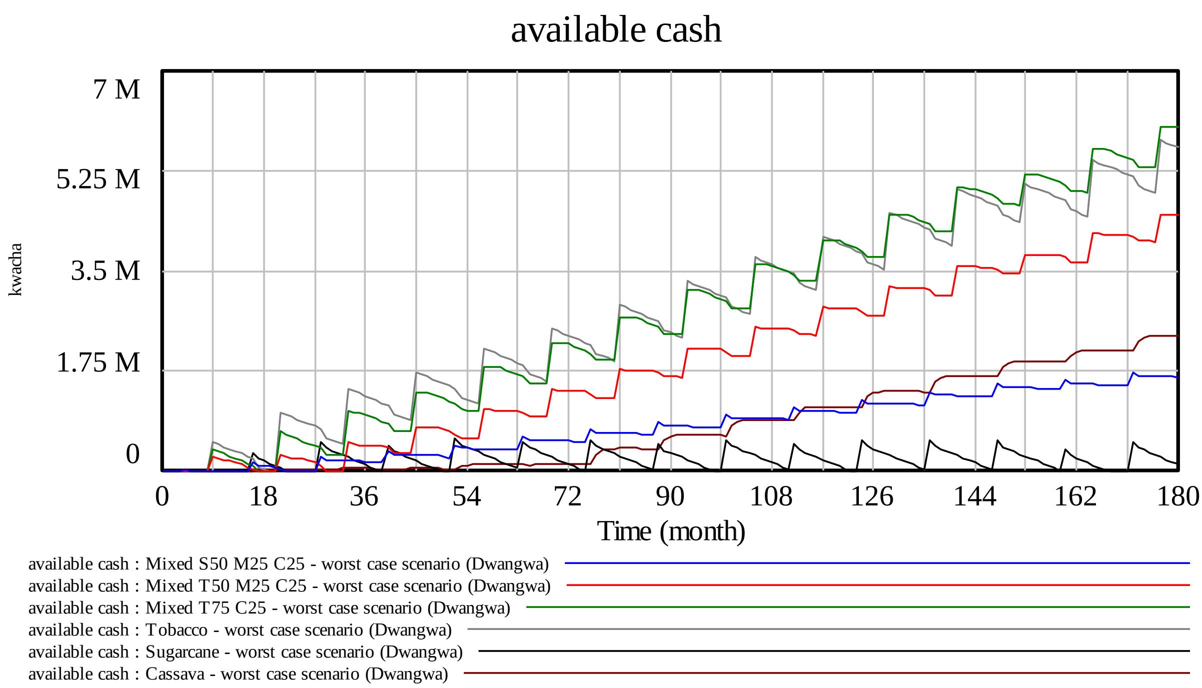

***Figure 5.4:** Accumulated wealth of top performers*

Household accumulation of wealth is observed with three of the mixed cropping patterns. Total earnings amounted to roughly MWK 1.6 million, MWK 4.5 million, and MWK 6 million for S50:M25:C25, T50:M25:C25, and T75:C25 respectively. This equates to yearly earnings of R2100 (USD 150), R6000 (USD 430), and R8000 (USD 570) over and above the household's yearly food expenditure and bare minimum expenses. Accumulated cash reserves for best performing mixed and monocropping patterns are shown in **Figure 5.4**.

5.2.2 Best-case scenario

For the best-case scenario, the area farmed was set to 1.4 ha, the initial capital was set to MWK 500 000 (R10 000 or USD 710) and the fertiliser subsidy was set to 70% of market cost. Additional assumptions were made for the growing of sugarcane and tobacco in accordance with the best-case scenario. Sugarcane farmers were deemed to be trust members, with access to irrigation and inputs by virtue of the services rendered to trust members by the respective farm management companies. Tobacco farmers were deemed to be IPS farmers with access to inputs on credit through contractual agreements.

5.2.2.1 Monocropping

Monocropping with any of the 5 crops lead to households being able to meet their daily DER under the best-case scenario. Tobacco farmers accumulated the most wealth over the 15-year simulation, followed by cassava farmers, sugarcane farmers, potato farmers, and the maize farmers (see **Figure 5.5**). The maximum income achieved was MWK 44 million which translates to about R60 000 (USD 4200) per year or about R4900 (USD 350) a month.

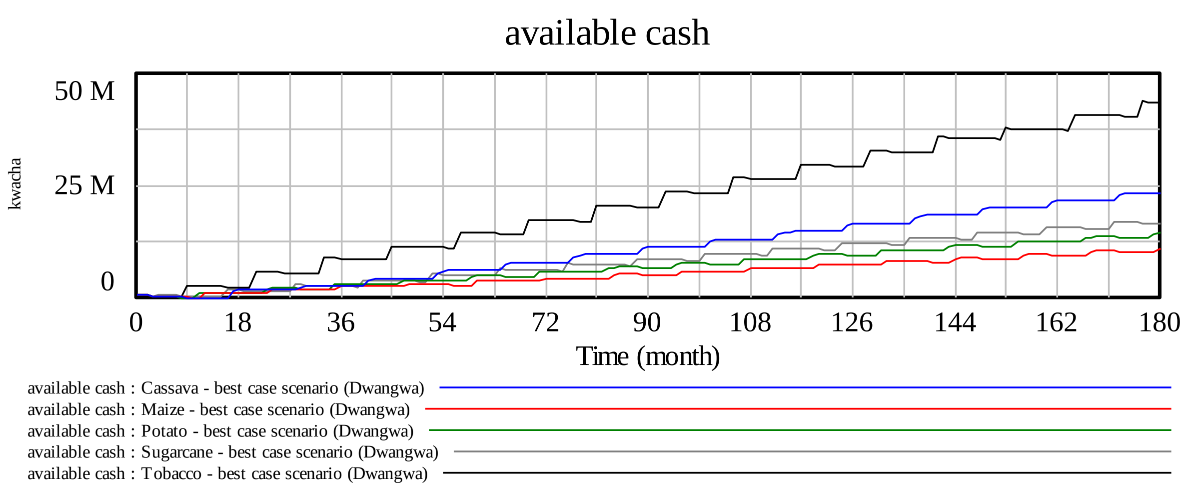

***Figure 5.5:** Monocrop total earnings for best-case scenarios*

5.2.2.2 Mixed-cropping

All the crop combinations proposed lead to households able to support their daily DER over the simulated period. The highest accumulated earnings were achieved by households that adopted the cropping pattern T75:C25. Next best earnings were achieved by T50:M25:C25, S50:M25:C25, S75:C25, and M75:C25 respectively. Earnings are shown in **Figure 5.6**.

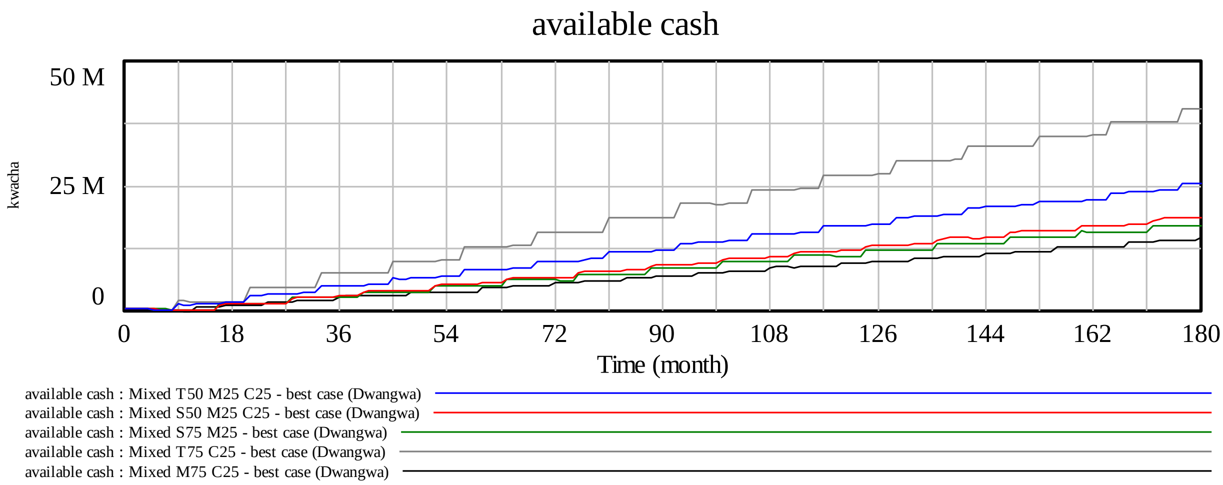

Figure 5.6: *Mixed cropping earnings for best-case scenario*

5.2.3 Most likely scenario

The most likely scenario saw farmed land set to 0.8 ha, starting capital set to MWK 50 000, and no government subsidies in effect. The additional assumptions made for sugarcane and tobacco farmers were based on the most commonly observed occurrence. Sugarcane farmers were assumed to be members of a trust with access to management services and inputs but without access to functioning irrigation (Mathias, 2017). Tobacco farmers were assumed to be IPS farmers forced to take compulsory loans and make loan repayments upon leaf delivery (Drope *et al.*, 2016).

5.2.3.1 Monocropping

Under most likely conditions, households that plant maize are unable to meet their DER in most years. Households who plant potatoes, cassava, sugarcane, or tobacco can maintain their required DER. With the exception of households engaged in maize monocropping, all other households begin to overcome their food expenditures and accumulate earnings. Households engaged in tobacco production earn the most over the 15-year period, they are followed by households cultivating cassava, sugarcane, and potatoes respectively. The maximum earnings, that which is achieved by tobacco farmers, is MWK 14,8 million. This translates to less than R1650 (USD 120) per month for a household of 4.6 people.

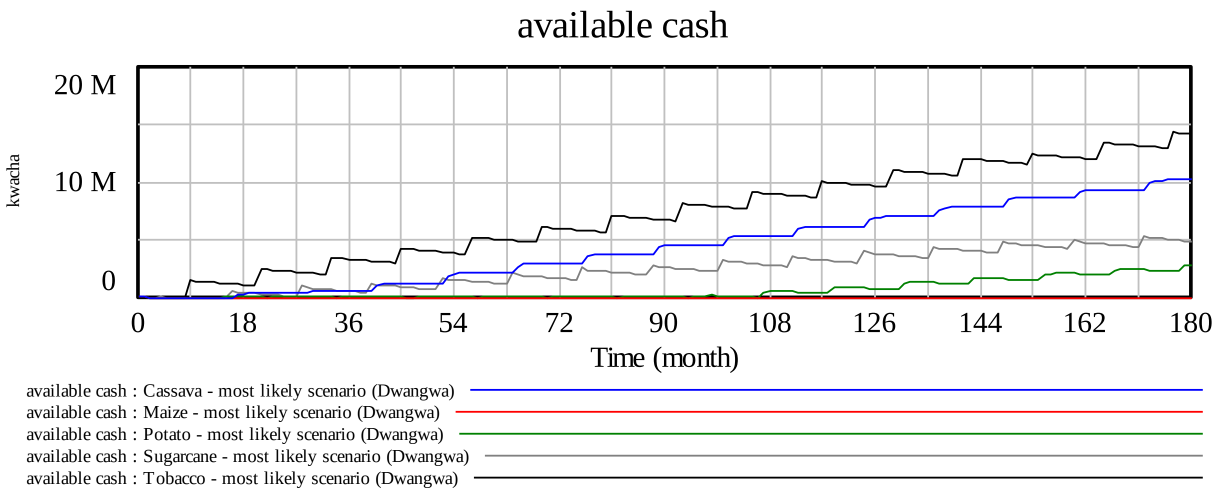

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Figure 5.7: Monocrop earnings for most likely scenario

5.2.3.2 Mixed-cropping

Planting 0.8 ha of land with any of the strategic combinations 6 – 10 proposed in **Table 4.7** yields enough food and/or income to maintain household consumption at the daily DER. Accumulated earnings are highest for the T75:C25 cropping pattern, this is followed by the T50:M25, S50:C25, S75:M25, and M75:C25 cropping patterns respectively. Highest earnings of MWK 15 million are attributed to the T75:C25 cropping pattern. This equates to earnings of R20 000 (USD 1430) per annum. Earnings for mixed cropping patterns can be seen in **Figure 5.8**.

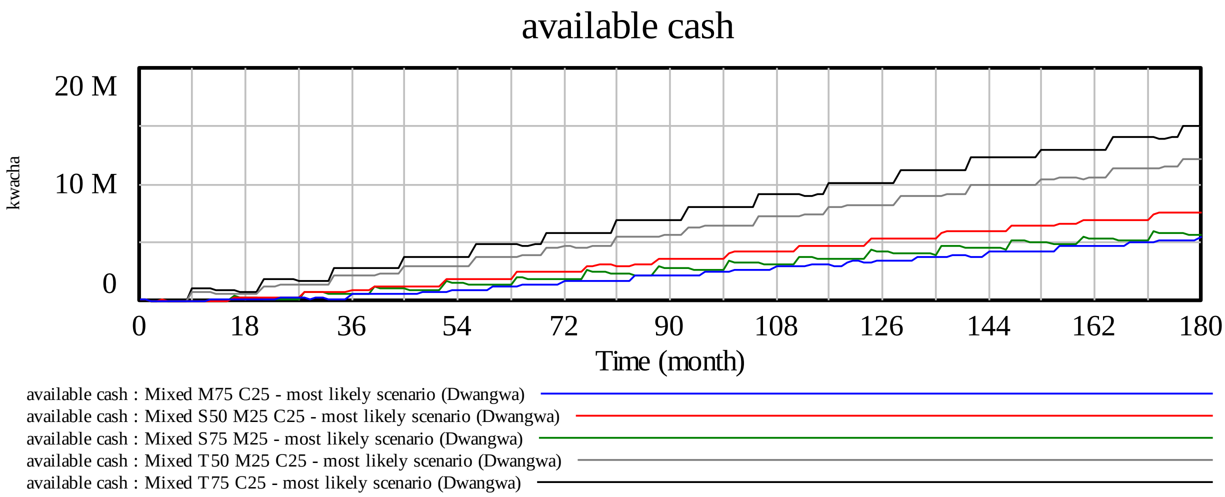

Figure 5.8: Mixed cropping earnings for most likely scenario

5.3 Analysis of results

5.3.1 Climatic suitability

Crop performance in Dwangwa is largely dependent on the climatic conditions. Under monocropping strategies, the crops that lead to the highest cumulative earnings and sustained levels of food consumption are cassava and tobacco. It is well documented that the region is especially suited to cassava cultivation. Agreement between the model results and the on-the-ground reality add to model validation (Benson *et al.*, 2002). The Dwangwa region is not perfectly suited for tobacco production climatically and this was evidenced in the yields. Yields between 1 and 2 t/ha were achieved by various households under the different scenarios. This falls short of the 3.5 – 4 t/ha often achieved by commercial farmers. Where yields of 1 t/ha are a result of insufficient inputs and unfavourable climatic conditions, yields of 2 t/ha are likely a result of only the unfavourable climatic conditions. In the case of Dwangwa, it is a result of too much rain. It must be noted that based on historical observations, 2 t/ha would be considered a good yield for smallholder Malawian farmers. The average yield for smallholder tobacco farmers is often below 1 t/ha (Jaffee, 2003).

High rainfall means that Dwangwa is also well suited to the growing of sugarcane. Yields between 70 and 85 t/ha were consistently achieved under rainfed conditions. This is in contrast to commercial farmers, in this case, Illovo, who regularly achieve in excess of 120 t/ha of cane. Under the climatic conditions in Dwangwa, maize grows relatively well. However, it is better suited to a drier climate and as such is occasionally impacted by excess rainfall in the region. Simulated results show that in the fourth year of the simulation, maize yields were impacted dramatically by high rainfall.

It is no secret that climatic conditions strongly influence crop suitability to a region. But, if the model is to be used as a tool for determining the performance of various crops in various regions, it must reflect this influence. To illustrate this effect, and the relative advantage certain climatic areas have to the cultivation of particular crops, a simulation was run for Nchalo. Nchalo is in Southern Malawi and is the site of the Illovo's second sugar mill. The climatic conditions are significantly different. Yields for both rainfed sugarcane (**Figure 5.9**) and maize (**Figure 5.10**) are shown at the two sites.

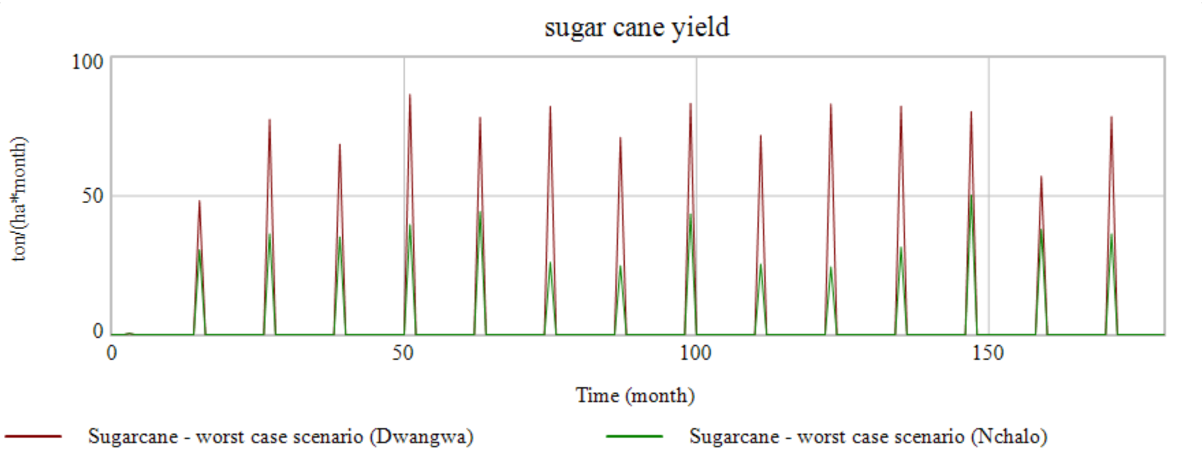

Figure 5.9: *Rainfed sugarcane climatic condition comparison*

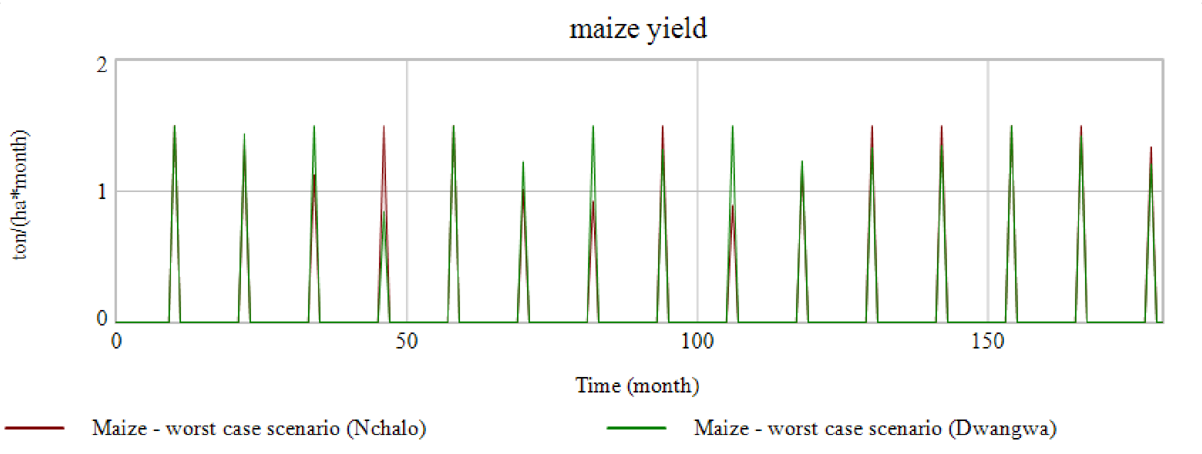

Figure 5.10: *Rainfed maize climatic condition comparison*

As suggested in **Figure 5.9**, it is not economically viable to grow rainfed sugarcane in Nchalo. Because of the limited rainfall, all sugarcane grown in Nchalo is irrigated. While Nchalo's climate does not lend itself to the growth of rainfed sugarcane, maize yields in Nchalo are unaffected by the drastic difference in precipitation. This highlights the fact that a blanket solution for Malawi's food insecurity issues might not exist in the form of a single crop or cropping patterns. Instead, climatic conditions, and other physical parameters not dealt with here, need to be reviewed carefully before crops or cropping patterns are encouraged. This might seem obvious, but Malawi has a history of encouraging maize production in regions where it is not well suited or where other crops might offer a far better prospect. As evidenced by the results of the baseline scenario, this can have drastic consequences on household consumption, earnings, and ultimately a household's level of food security.

5.3.2 Fertiliser response

The results of the simulation show that households that mono-cropped with maize suffered severe food shortages for the worst-case and most likely scenarios. In the best-case scenario, cultivating maize as a monocrop is still the least favourable outcome, however, it fares significantly better relative to the other crops. The opposite is true for cassava. Cassava performed well in all scenarios, however, in the best-case scenario it performed the least well relative to its performance against other crops in other scenarios.

This indicates that maize responds better to fertilizer than cassava. It also indicates that cassava is less dependent on fertilizer to produce yields. Under worst-case conditions, where households are struggling to meet their DER, limited money is available for the purchase of inputs. With insufficient inputs, a more hardy or resilient crop is desirable. Under best-case conditions, if it is assumed that a household has sufficient resources available for the purchase of inputs, then a crop that responds well to inputs is desirable. This is still subject to climatic conditions. A crop's suitability to a particular household is, therefore, a function of both climatic conditions and the crop's response to fertilizer.

5.3.3 Access to credit

If a crop's usefulness to a household is dependent on its response to fertilizer, then whether a household has access to inputs or not is a crucial factor in determining whether a crop is appropriate for cultivation or for revealing the effect of incorrect cropping (ICs included) on food security. Access to inputs is in turn dependent on two things; household capital, and in the absence of sufficient capital; access to credit.

Access to credit in Malawi is notoriously low (Jaicaf, 2008). The NSO (2012) report that only 14% of households have any interaction with the credit market. Both sugarcane and tobacco farming provide increased credit options to smallholder farmers. However, these options take radically different forms. The magnitude of the impact of credit access on food security is unclear. The different impacts the various forms of agreements have on food security are also unknown.

5.3.3.1 Independent vs contracted farmers (IPS)

Households who opt to engage in tobacco farming can do so in two manners. Tobacco farmers who engaged in the IPS contractual system saw increased levels of food security and wealth during the first years of cultivation. Those who opted to farm independently saw better long-term accumulation of wealth. The higher levels of success among IPS farmers in the early years of the simulation are a result of IPS farmers having access to fertilizer from the first season of planting.

Higher levels of long-term earnings achieved by independent farmers are a result of the premium IPS farmers pay on inputs and the cost of input loan repayments.

i. Effect of compulsory loan packages

These loan packages are the subject of some controversy. They have been criticised for the inclusion of goods not directly related to the growing of tobacco and the fact that many of these loan packages are compulsory. To this end, a further hypothetical scenario is tested here to determine the potential impact of a voluntary loan. Results of all three scenarios are shown in **Figure 5.11**. Interestingly, a hypothetical contractual agreement between the leaf companies and grower where an input loan is voluntary and not compulsory leads to the highest earnings for the smallholder.

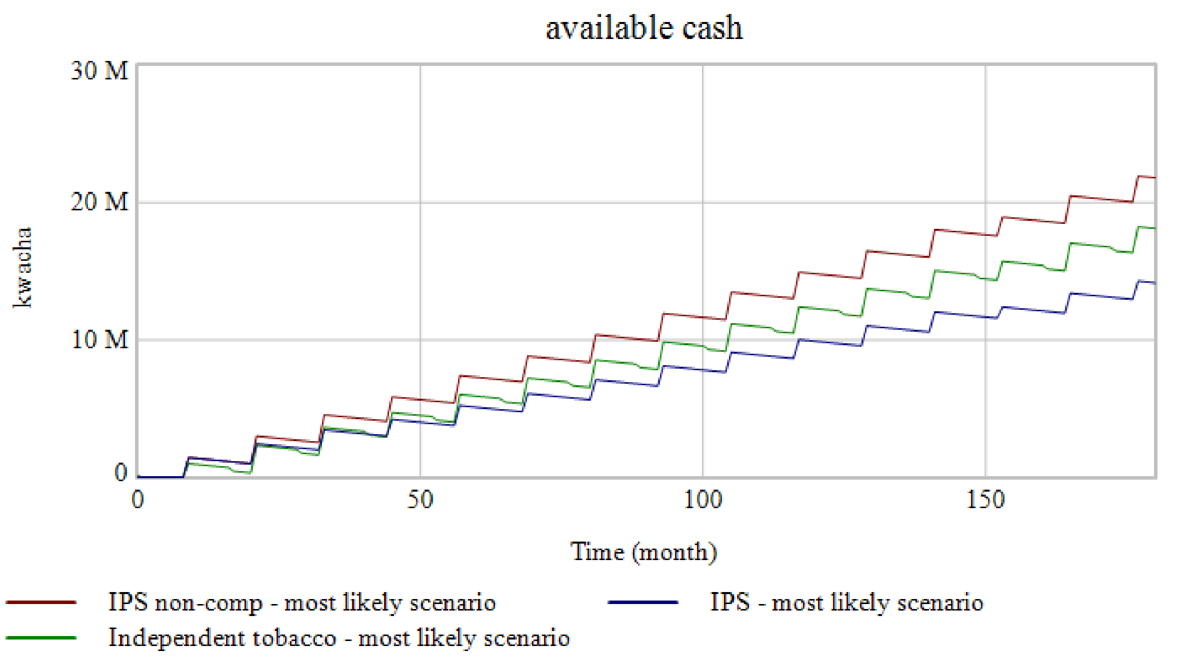

Figure 5.11*: Tobacco loan agreement performance*

5.3.3.2 Trust membership

With the exception of a few very large landowners who have contractual arrangements with Illovo directly, all other sugar growers are forced to work through associations who mediate transactions between the mill and the growers. This effectively means that all smallholder farmers must engage with associations if they are to supply sugarcane to an Illovo mill. Associations operate dry land and irrigated farming systems, however, less than 30% of the land operates under irrigation.

A relatively large amount of capital is required for an initial investment into irrigation systems. Associations managing irrigated land, only the DCGL and Tipate in Dwangwa, fit the bill and repayments are deducted from the farmer's earnings from cane delivery to the mill. All outgrower schemes in Nchalo are irrigated. A hypothetical dry land scheme for Nchalo is included for comparison. The performance of the different schemes is shown in **Figure 5.12**.

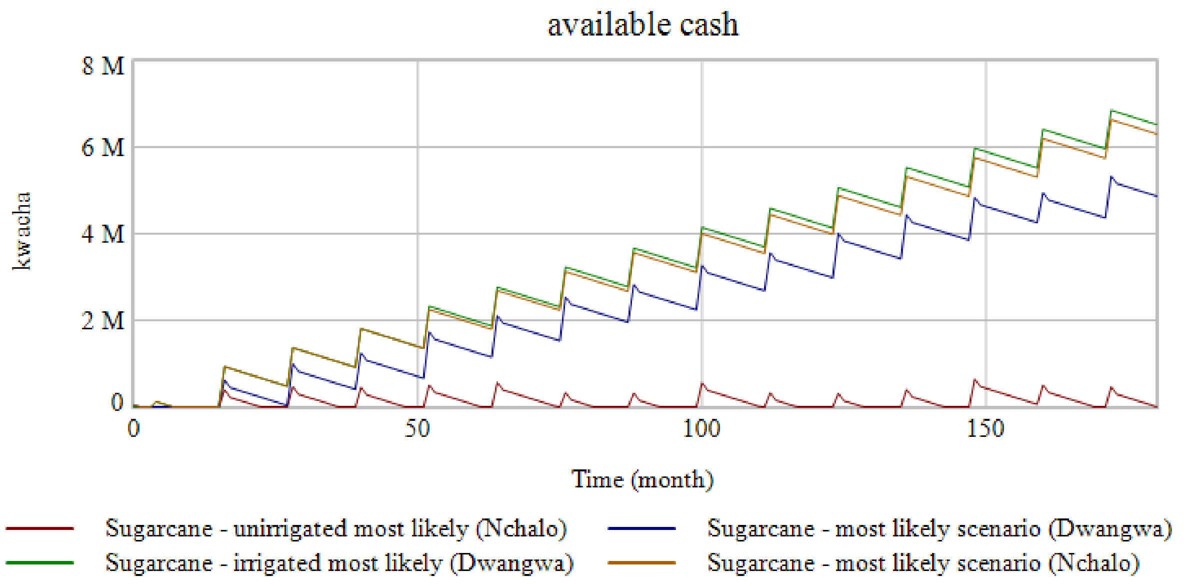

***Figure 5.12**: Sugarcane scheme performance*

As is well established, rainfed sugarcane farming is not viable in Nchalo. Sugarcane cultivation in Nchalo is only made possible through access to credit. This access to credit allows for an entire industry to exist which otherwise would have been impossible climatically, opening new avenues for revenue and livelihoods. Results of this simulation suggest that access to credit, a result of sugarcane expansion in Nchalo, propels sugarcane cultivation to the second best performing crop at providing food security to smallholder farmers.

In **Figure 5.12** it is seen that despite the high rainfall in Dwangwa, the returns on irrigation investment for sugarcane make the effort worthwhile. Furthermore, the benefits of irrigation in Dwangwa are thought to be better than reflected in this simulation. This is because average irrigation maintenance costs are used in the model, in reality, pumping costs are likely to be cheaper in Dwangwa owing to much of the sugarcane's water requirements being met by the high rainfall.

A new comparison of crop performance in Dwangwa under the most likely scenario shows that for the first 5 years of the simulation, irrigated sugarcane replaces cassava as the second highest performing crop.

5.3.3.3 Effect of initial capital

The value of the initial capital a household has access to is a major driver in this model of whether a smallholder farming family manages to purchase inputs during the first year. The ability to purchase inputs just once can have a drastic impact on household food security for many years after. This lasting effect of inputs purchased is illustrated in **Figure 5.13** and **Figure 5.14**.

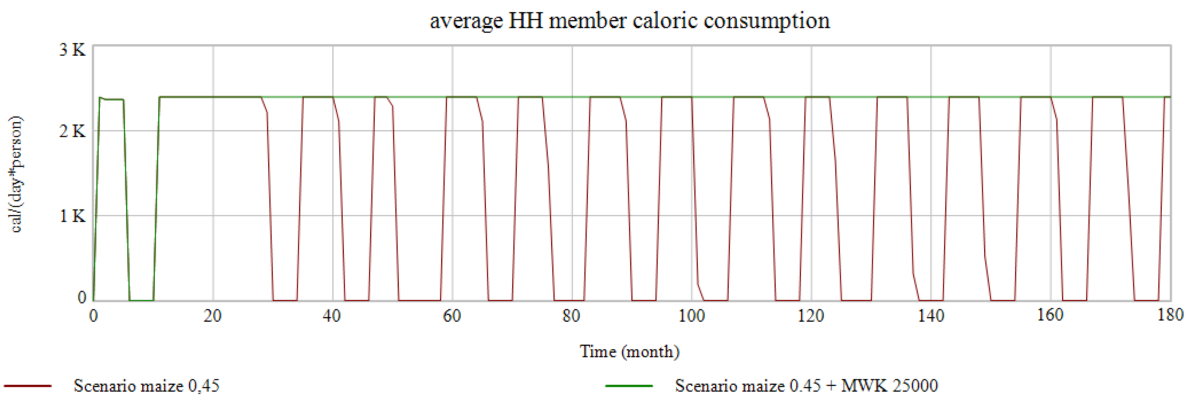

Figure 5.13: Effect of initial capital on household consumption

'Scenario maize 0.45' is a scenario whereby a farmer (farmer A) has 0.45 ha of land and is monocropping maize. The smallholder farmer was given a certain amount of starting capital. The other scenario is the same with regards to location, landholding, and crop cultivated. However, the smallholder farmer in the second scenario (farmer B) was given MWK 25 000 in addition. This equates to an extra R500 or just USD 36. The impact of this additional starting capital is astounding.

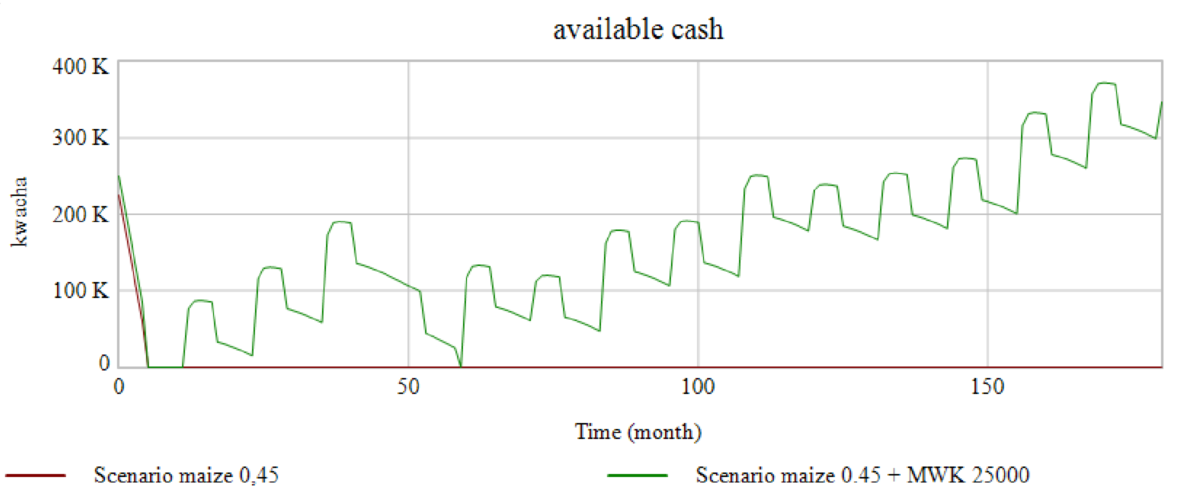

Figure 5.14: *Effect of initial capital on accumulated earnings*

Both farmer A and farmer B can support their families' food requirements initially. Analysis of the results reveals that Farmer B, however, is also able to buy some inputs for the upcoming season with his extra $36. Yields of the following season are high enough that both households can maintain their DER, but the higher yields achieved by Farmer B mean that he has surplus food which he can sell. The income from food sales allows him to buy fertilizer for the next season whereas farmer A cannot.

In the next season, climatic conditions were such that farmer A did not achieve the required yields needed to feed his family. Farmer B maintained high enough yields to feed his family, buy inputs, and save a little money. The pattern continues, and farmer B slowly builds up savings while farmer A and his family continue to face extreme food shortages.

In the fourth year, there is a drought. Yields for both farmers effectively halve and despite farmer B's use of fertilizer he does not grow enough food to support his family. In this case, farmer B is fortunate to have enough savings for his family to eat and to purchase inputs for the following season. However, if the drought had come one season earlier he would have been destined to the same fate as farmer A for the remainder of the simulation.

The results of these two scenarios are powerful in describing the impact that access to inputs can have on smallholder food security. They also show the devastating impact that climate variability can have on smallholder farmers in the absence of irrigation. It also thrusts the importance of household decision making into the fray. In order to keep track of the total accumulated earnings, this model does not simulate the purchase of miscellaneous items and other expenses beyond that which was reported as the minimum non-food expenditure of Malawi's poorest households by the NSO (2012). Therefore, it is likely that in the real system farmer A spent some of his savings and would not have had enough money to support his family through times of crises. Financial education is important to encourage smallholder farmers to act wisely with their money.

5.3.4 Effect of subsidies

For smallholder farmers who planted food crops and those farmers who were engaged in IC cultivation but remained independent, the impact of subsidies was positive. The effect of subsidies operated in a similar manner as the effect of altering the initial capital. Successful farmers benefitted from subsidies and many farmers with less land were propelled from a state of continued food insufficiency to one in which the household's DER could be met.

The form of the subsidy matters. Simulation results showed that some food-crop farmers could not take advantage of the subsidy program. Under Malawi's Farm Input Subsidy Program (FISP), government subsidies reduced the cost of fertilizer to 64% of the commercial market price in 2006. However, to take advantage of cheaper inputs, a farmer must have at least some money. Smallholder farmers who could not grow enough food to eat, let alone sell, were consistently cash-strapped and no amount of increase in subsidies allowed them to purchase inputs. Thus, exceptionally poor households would benefit if they could receive the equivalent value of the subsidized portion of fertilizer.

Smallholder farmers engaged in contractual agreements with either the leaf companies (IPS) or with sugar associations did not benefit from subsidies. IPS tobacco farmers were still required to receive input packages on loan from the leaf companies and the cost charged by the associations to the sugar farmers for services rendered remained unchanged.

The role of subsidies is similar to that of increasing access to credit, both aim to bring the cost of inputs within reach of the smallholder farmer. Subsidies provide a method for the government to distribute value to farmers without handing out hard cash. However, simulation results showed that providing farmers with capital was more effective in leading to long-term food security, granted this was only in true when farmers purchased inputs with the money. Following this logic, the handing out of much smaller, yet free fertilizer packages to exceptionally poor farmers at the same cost to the government might be a more effective alternative form of subsidizing inputs.

On the other hand, contract farming is an effective system to ensure a farmer's continued access to the inputs required. In fact, results indicate that having access to inputs is more important than the cost of the inputs. Small differences in input cost are lost in the results of much higher yields.

5.3.5 Effect of mixed-cropping

This model simulates mixed cropping by attributing a percentage of the land to different crops. This is not necessarily the same as intercropping, which is the planting of different crops often in alternating rows, that complement each other in terms of the nutrients drawn and given to the soil. Instead, this simulation looks at mixed crop growth on different or adjacent plots of land that might complement each other as a result of a number of other factors.

5.3.5.1 Food is cheaper to grow than buy

In the worst-case scenario tobacco is the best performing monocrop. Despite the fact that cassava performs half as well as a monocrop in this scenario the mixed-crop combination of T75:C25 is the best performer in this scenario. Clearly, this is not simply a case of one plus one equals two. Further analysis reveals that the tobacco farmer, despite earning more money at each harvest, has to spend money on food. The T75:C25 farmer grows food in addition to tobacco and therefore needs to buy less or no food each season. The results show that food is cheaper to grow than to buy, and this is certainly validated by observations in the real system.

5.3.5.2 Harvest to planting window

Under the worst-case scenario, sugarcane performs averagely, and maize performs poorly in terms of supporting the household's DER. On the other hand, cassava performs better than both maize and sugarcane in terms of supplying food for a household to meet their DER under the worst-case conditions but there is no worthwhile accumulation of money until the beginning of the seventh simulated year. However, planting sugarcane, cassava, and maize on 50, 25, and 25 percent of the land respectively yields an interesting result. The mixed cropping pattern S50:M25:C25 outperforms all three of its constituents for the first 10 years of the simulation. Once again it seems illogical that mixing worse performing crops with better-performing crops leads to cropping combinations that outshine the better-performing crops. Analysis reveals that the length of time between harvesting and planting plays an important role in these dynamics. This is because planting time is where much of the fertilizer required is purchased and used. Results of the simulation show that when there is a short time between harvesting and replanting, the farmer has enough money to buy inputs. When there is a long time between harvesting and planting, a farmer's savings have often dwindled and there is seldom enough money left over for the purchase of inputs under worst-case conditions.

In the case of the mixed cropping pattern S50:M25:C25, planting this combination of multiple crops means that planting times are staggered and the times of input requirements are more likely to overlap with periods in which the farmer has money available for the purchase of inputs.

Low-income values in the worst-case scenario mean that **Figure 5.4** has sufficient resolution to see the patterns of income and expenses for each crop or mixed-crop clearly. The effect of the amount of time between harvesting and planting is seen in **Figure 5.4**. Crops and mixed-cropping combinations that have a smaller window between harvesting and planting have significantly less oscillation in their curves.

5.3.5.3 Multiple benefits of staggered cropping cycles

The last three years of the simulation, from month 144 to month 180, Dwangwa experiences drier years. A comparison between cultivating only tobacco against the mixed-cropping pattern T75:C25 in **Figure 5.4** shows that the household that grew only tobacco was initially doing better than the household that grew both tobacco and cassava. In the final three years, however, the household that grew cassava in addition to tobacco fared better during the changing weather patterns and drier conditions. Analyses of the model's results show that growing multiple crops is an effective strategy to mitigate risk.

In fact, further analysis of the results shows that the benefit is twofold. Growing multiple crops aids in defending against both macro and microclimatic variability if the crops are chosen such that they respond to water-stress differently, have slightly different optimal climatic conditions, and have different cropping cycles. This essentially means that two eggs can be split between 4 different baskets for risk purposes if the crops chosen for cultivation are chosen well.

i) Planting crops with different cropping cycles help protect the farmer against long-term rainfall variation.
ii) Planting crops that respond to water-stress differently help protect the farmer against short-term rainfall variation.
iii) Planting crops that have slightly different optimal water requirements protect the farmer against both long-term and short-term rainfall variations.

5.4 Limitations and assumptions

George E. P. Box famously wrote that all models are wrong, but some are useful. Models are not 'truth' and cannot exactly replicate the real system, instead, they are a simplified representation of reality. The level of detail and complexity captured in the model is known as model fidelity. A more complex model is expected to have greater validity and give more detailed results, however, it will also require more resources, be more likely to contain errors, more difficult to understand, and less portable (Brooks & Tobias, 1996). Where the real system cannot be modelled exactly, assumptions must be made. In some cases, aspects of the system are excluded from the model completely if a model is deemed to achieve sufficient accuracy without them. This leads to model limitations. The model's limitations and the assumptions made by the modeller are discussed here. The conclusions and recommendations that can be drawn from the simulation's results are subject to the assumptions made and the model's limitations.

5.4.1 Resolution

The temporal resolution chosen for the model was at the monthly level. This was chosen as the largest time interval, for computational and resource reasons, that could sufficiently capture the system's dynamics and allow for adequate model fidelity.

This leads to two model limitations. The first is that rainfall is simulated based on a normal distribution of the monthly rainfall. This means that daily and weekly variations in climatic conditions are not captured by the model. Crops are dependent on both the amount and the distribution of the rainfall. If two crops both receive 100mm of rain in a month, but one receives it over three consecutive days and the other for 15 days every second day, their yields would be very different. However, the temporal resolution at the monthly level is sufficiently fine to capture seasonal fluctuations in rainfall and to accurately distinguish between rainfall that falls during a crop's growing period and that which falls outside.

The second limitation is that human decisions modelled within the simulation can only be revisited monthly. Thus, decisions to buy or sell food by households within the model must be made with a full month in consideration.

5.4.2 Data limitations

There were some data that were simply not available in the literature and could not be obtained on site. Data quantifying the labour requirements for different crops based on Malawi's farming methods was not available nor was data available regarding the cost of labour in the smallholder farming sector. This is primarily because labour in Malawi takes many forms. Labour – ganyu in Malawi – can be paid for, can be reciprocal, can take the form of child labour, and almost never conforms to Malawi's minimum wage laws. Therefore, the cost of labour to the farmer is very difficult to quantify. Furthermore, this model aims to capture food security issues as they relate to Malawi's smallholder farmers, most of which do not have access to more land than what the family unit can handle. Thus, labour is excluded from the model and this limits the model's accuracy.

Information regarding the Dwangwa's sugar associations was available, albeit the data was ambiguous. The information that was ambiguous pertained to the payment schemes and services rendered by the sugar associations such as the DCGL. To clarify the conflicting information, the author scheduled meetings with members of the DCGL and the milling company, Illovo, whom the DCGL mediates on behalf of with the outgrowers. The DCGL would not divulge specifics of the fees charged to farmers. These details have not been made clear to the milling company either (Mathias, 2017). To this regard, it is worth noting that the sugar associations, the DCGT and DCGL package in particular, have been accused of being a mechanism through which the political elite take advantage of government initiatives and rural farmers to accumulate wealth (Chinsinga, 2016). Thus the author has made use of the only available information regarding the structure, roles, and dynamics of these systems as described by Chinsinga (2016) and CISANET (2013). The reliance on only two sources, in which there is still much to be desired, could potentially limit the fidelity of this model.

5.4.3 Market trends

Effects of the movements of the global economic climate and market trends have been excluded as a driver of the model. This means that the prices paid for food, sugar, and tobacco are not subject to change as a result of global changes in supply and demand. Instead, prices are determined by the median price over recent years. This is could limit the model's accuracy as while Illovo, the milling company, buffers the effect of the global market and offers consistent cane prices to farmers, the price of tobacco fluctuates. This is because much of Malawi's sugar is sold domestically, about 60% (Corporate Citizenship, 2014), while almost all tobacco is exported. The model does not capture tobacco's increasing status as a pariah industry and the impact this might have on tobacco prices. This could impact the value of this study's results in the future. However, it must also be remembered that these values can be updated at any point in time, generating new results. Similarly, fluctuating exchange rates, currency devaluation, and inflation are not modelled and considered excluded variables as listed in **Table 4.1**.

5.4.4 Physical factors

There are a number of aspects of the physical system which were also considered excluded variables. The model does not account for the potential impacts of climate change within the crop models. This was deemed to be beyond the scope of this model.

Arguably the model's greatest potential limiter of accuracy stems from assumptions made within the crop models. The temporal resolution and its effect on rainfall distribution have been covered in part. Rainfall, true to the real system, is a major driver of crop yields. However, the crop model relies on an input value that tracks the rainfall that fell during the crops growing cycle. This value does not capture the distribution of the rainfall across the growing period. Distribution has a large effect on yields. To constrain the effect of this limitation a relationship was formed between the amount of rainfall that fell during a crop's growing cycle and the crop's expected yield from historical rainfall and yield data. In order to isolate the relationship between rainfall and yields from the use of different amounts of fertilizer, different farming practices, and even the use of different cultivars over the years the author turned to the available literature on the subject matter. Yield-rainfall curves for each crop were averaged from multiple studies. Rainfall-yield field test results were weighted according to the similarity of climatic conditions with that of Malawi's. Once the curve's shape had been formulated, the curve was shifted to fit values corresponding to each location's yields. Because historical data were used, the effect of variability in rainfall distribution over the crop's growing cycle is covered within the relationships formed.

The yield-rainfall response curves were validated through results for potential yields and yield gaps returned by EarthStat's cropping database using Dwangwa's coordinates as an input (EarthStat, 2017). The relationships were further verified with observations within the real system. On the other hand, yield-fertilizer response curves are well documented in the literature, however, existing soil parameters were not taken into account beyond checking for crop suitability.

Significant declines in sugarcane yield for subsequent ratoon cropping was taken into account by using average yields over the crops full ratoon cycles.

5.4.5 Social dynamics

An assumption was made that the number of people in a household remains constant over the 15-year simulation period. Even though this is unlikely in the real system, this assumption was made to ensure the model was the best representative of any given household at any given time in Malawi. Therefore, it was decided that the average rural household size would be used (NSO, 2012). The household size remains the same even through exceptional circumstances of prolonged extreme hunger. Household members cannot pass away as a result of starvation.

An important assumption made concerns a household's response to bankruptcy. The farmer's ability to plant the ICs of sugarcane and tobacco, where inputs are obtained on credit, remains unaffected. However, bankruptcy would affect a farmer's ability to buy seed for his fields. There are a number of coping mechanisms adopted by Malawian smallholder farmers in the face of bankruptcy (Whiteside, 2000). An example of a coping mechanism common in Malawi is that of ganyu. A farmer who is without money will look for work as a labourer. In many cases his employer might not be able, or willing, to pay him in cash but the labourer will receive payment in the form of cassava or sweet potato cuttings. A farmer can then plant these cuttings on his own land and effectively recover from bankruptcy to some extent. Other coping methods include cutting and selling wood for construction or cooking and receiving help from extended family or village members. It is based on a review of these coping strategies that a farmer is effectively allowed to replant despite bankruptcy within the model.

The final decision variable within the model is based on the assumption that a household will choose to purchase food over paying for other non-food expenses, such as purchasing inputs or repaying loans, if the household is not meeting their required DER.

5.4.6 Food preferences

It is important that the results are interpreted in the context of food preferences. There is a strong cultural preference for meals based heavily on maize (Meerman *et al.*, 2015). In the case of monocropping with a food crop in the simulation, regardless of the household's accumulated wealth, the household will continue to meet their DER with that food crop. In reality, a household that sees an increase in accumulated wealth would see an equivalent increase in diet diversity. Where the preference, regardless of wealth, is for a maize-based diet – nsima is the local dish –

farmer's who plant only cassava or potatoes are unlikely to eat only cassava or potatoes unless the circumstances are extremely dire. This is not reflected in the model.

Furthermore, all of Malawi's food preferences are not encompassed by the three food crops simulated here. In the real system, a variety of other crops are grown to supplement smallholder DERs. Only the most important staples are simulated in this model and household food security does not reflect the presence of these dietary additions. This likely results in the model underestimating food security.

The cost of food has been pegged as a price per calorie constant. This value does not reflect the cost of any type of food in particular but rather is an aggregated value based on the minimum amount of calories required to support the average household member, the calories in a typical Malawian food basket, and the cost of a food basket adjusted for inflation (NSO, 2012). Thus, a farmer who grows cassava is getting paid the same price per calorie as a farmer who grows maize despite a strong cultural preference for maize. This affects the accuracy of wealth accumulation where food monocropping is concerned and is likely to overestimate the earnings of a cassava farmer.

Chapter 6: Study conclusion

Chapter 5 presented and discussed the results obtained concerning a variety of strategies and scenarios. The results were analysed, and different drivers of the model were identified, and their impacts on food security discussed. The assumptions made were stated and limitations of the model were discussed. This chapter concludes the study. The key findings are presented, and recommendations based on these findings, in the context of the study's limitations, are made to stakeholders. The chapter also reflects on the research question and objectives to determine whether they are duly addressed. Opportunities for further research are proposed and a reflection on the research effort is provided.

6.1 Key findings

The study's important findings are summarised here. These findings are the product of an in-depth analysis of the simulation results to determine the relevant system drivers. The role of ICs on these drivers and the role of the drivers on food security is highlighted.

Different place different crop

It seems an obvious finding that different crops have comparative advantages in different places, but Malawi's strong cultural preference for maize, at both government and personal levels, has led to the planting of maize in environments better suited to other crops. Results of the model confirm this comparative advantage. Cassava is incredibly well suited to the climatic conditions in Dwangwa and is a logical crop selection for smallholder farmers in this region. Sugarcane cultivation is not economically viable without irrigation in Nchalo. The expansion of ICs in Malawi allows for an increased variety of crops for selection. Sugarcane is a good alternative to cassava in areas that receive high rainfall, especially in areas where maize plants might drown owing to waterlogged soil.

From input independent to input dependent

Results show that farmers with little to no capital should begin cultivation operations by investing in crops that are less input responsive. Although this means that a farmer will receive less return on investment into fertiliser, it ultimately also means that the farmer will do better in the case that fertilizer cannot be acquired at all. This is purely a risk aversion strategy. The notion of no risk no reward holds true here, however, a smallholder farmer should not gamble on climatic conditions that are uncontrollable. The prospect of investing money and effort into crops highly dependent on fertilizer when fertilizer is not guaranteed is unwise. So too is the purchase of excessive amounts of fertilizer when rainfall is not guaranteed. It must be stressed that this is not an argument for planting crops that are unresponsive to fertilizer, this is an argument for not planting crops that are heavily dependent on fertilizer for any worthwhile yields. The seed for crops that respond highly to fertilizer, such as hybrids, is more expensive. This would be a waste of money for a smallholder farmer without the means to tend to such crops adequately.

As savings are accumulated, a farmer should progress from cultivating crops less responsive to fertilizer and more resilient to input and water stress (such as cassava) to crops that respond well to inputs (hybrid maize). True food security can only be achieved after this transition.

Credit deserves credit

Access to credit is crucial to changing the food security situation of smallholder farmers. The link between ICs and credit access is strong. The contractual agreements between certain leaf companies should not be compulsory, and contracts between the sugar associations and the outgrowers should be more transparent. Access to credit allows farmers to purchase important inputs, returning greater earnings, ensuring inputs can be bought again. This activates a reinforcing feedback loop that leads to increased food security. A lack of rainfall can halt this feedback loop. Where credit is sufficient to cover irrigation costs, the integrity of the loop is protected. IC cultivation influences credit access positively and credit access influences food security positively.

A discount to the penniless

The penniless man has no use for a discount. Results of the study show that the smallholder farmer who has no money cannot take advantage of subsidies in the way that even a farmer with little savings can. This shows the importance of a farmer supplementing his earnings with some form of off-farm income. A lack of savings can result in opportunities missed.

The effect of subsidies, however, must not be negated. Results show that while subsidies are potentially worthless to the destitute, they are still a lifeline to the poor. Subsidies are an effective mechanism to reach a large number of farming households and increase food production and regional food security. ICs affect subsidies in two ways. First, those engaged in contracted IC farming have access to inputs, therefore more subsidised inputs are available to those who need it most. Industries related to IC farming – sugar milling, and leaf processing – pay large sums in tax to the government, which aids in the financing of subsidy programs. Therefore, the relationship between ICs, subsidies, and food security is positive.

Hedge your bets

Mixed cropping is an effective risk aversion strategy and farmers should plant multiple crops. However, some cropping combinations are more complementary than others. Mixed cropping has many benefits. Mixed cropping leads to increased food security because:

i) Food is cheaper to grow than to buy.
ii) Staggered revenue streams mean that a farmer is more likely to have enough money from a recent harvest for the purchase of inputs for another crop.
iii) Planting crops with different cropping cycles help protect the farmer against long-term rainfall variation.
iv) Planting crops that respond to water-stress differently help protect the farmer against short-term rainfall variation.
v) Planting crops that have slightly different optimal water requirements protect the farmer against both long-term and short-term rainfall variations.

Cropping combinations that saw good results leading to higher levels of food security were T75:C25 and S50:M25:C25.

6.2 Recommendations to stakeholders

The quality of the conclusions arising from using the model depends upon the quality of the results, which is a combination of their accuracy and the extent to which they address the modelling objectives (Brooks & Tobias, 1996). Therefore, the assumptions made in the modelling process and associated limitations must be kept in mind when constructing recommendations from the simulation results.

6.2.1 Recommendation 1: concerning location

Agriculture extension officers and smallholder farmers must plant crops only which are well suited to the environment and climatic conditions of the region. On marginal land, only the most resilient of crops should be planted. Planting anything else, unless there is adequate access to fertilizers and irrigation, is foolhardy. This requires agricultural extension officers to be well versed in the suitability of different crops to their region of deployment and also the economic status of those who seek their advice.

6.2.2 Recommendation 2: concerning subsidies

Government should give careful thought to the use of subsidies and their expectations of the effect they think subsidies will have. Subsidies are an effective tool for reaching a large proportion of the population and increasing levels of food security nationwide. However, the effect will likely only be felt in the short term if the majority of farmers are only growing food crops. Understanding of the system reveals that subsidies lead to a large increase in food production, food becomes abundant in Malawi and the food price, especially that of staples, drops drastically. Farmers can therefore not accumulate wealth in this manner. A household then only has surplus food to sell when all other households also have a food surplus. This leads to increased levels of food security but cannot lead to the accumulation of wealth. Without the accumulation of wealth, when the subsidies stop, so too do the higher levels of food security.

A solution to this would be to develop sufficient channels for the acquisition, purchase, and export of food to foreign markets. However, in the context of hundreds of thousands of smallholder farming families with excess food, poor infrastructure, no seaport, perishable goods, and the need for an accepting market, this would be a logistical challenge. A second solution would be the purchase and storage of grain by the government in an effort to keep prices higher to protect farmers. Grain could then be released upon cessation of the subsidies. This would be a careful balancing act and serves no real purpose other than to prolong the effect of expensive subsidies.

However, the markets for the export of ICs are already well established. Subsidies for IC farmers would result in greater earnings for the farmers and greater earnings of foreign exchange for Malawi. However, the government would have to work closely with leaf and milling companies to ensure processing and handling capacities have not yet been reached and that markets for the extra produce can be found.

Does this study advocate for the use of subsidies? The answer is yes if the goal is an immediate increase in food security. If the quest is for a more long-term and sustainable solution to the research problem, then further policy changes and accompanying strategies are required. This would require a private-public sector partnership.

6.2.3 Recommendation 3: concerning mixed cropping

Smallholder farmers should be encouraged to cultivate multiple crops, some of which should be food crops. This makes financial sense because food is cheaper to grow than to buy. This also ensures that Malawi as a nation is less likely to have a national food deficit and can avoid costly imports.

Mixed cropping should also be encouraged to ensure farmers are well protected from climate variability in the absence of irrigation. This is both because crops have different cropping cycles and because all crops have different (sometimes slight, other times major) optimal water requirements and maximum and minimum thresholds which they can endure. Finally, mixed cropping also leads to staggered income because some crops – such as sugarcane and cassava – can be harvested at the end of the year, while others – maize, tobacco, potatoes – are harvested at the end of the rainy season. This reduces the amount of time between receiving money and times of require input purchase.

6.2.4 Recommendation 4: concerning credit access

The creation of an institution geared towards offering micro-loans coupled with knowledgeable agriculture extension officers should be explored. Access to credit is imperative to achieving pro-poor growth and reducing poverty. It is understood that Malawi has a history of loan recovery issues and that agricultural lending has declined significantly as a result of poor credit discipline. However, the fact remains that credit access is a fundamental pathway to food security in Malawi. Thus, to ensure lenders are successful in loan recovery, the institution cannot be a purely financial one, rather it needs to be coupled with teams capable and responsible for agricultural oversight.

The use of private farm management companies, such as those that operate in the sugar sector, is another alternative to overcoming the credit access obstacle. These need to be fully private to avoid becoming pawns in political games, and ideally, multiple should exist to ensure competitiveness and smallholder farmers are not taken advantage of.

6.3 Opportunities for further research

A number of areas have been identified for future research. There are two broad categories in which further research can be classified with respect to this study; improvements within the model and then research which falls within the scope of the research problem but outside the scope of the simulated model.

Improvements within the model scope

An area where there is ample room for improvement is in the crop sub-models. The current sub-model is hyper-simplified and although it gives realistic results it fails to capture the intricacies of the effect of rainfall distribution at the micro-level on crop yields fully. Furthermore, the effects of pre-existing soil conditions, total evapotranspiration, and pests and diseases are not modelled. The inclusion of this would affect the resilience of crops in the model and possibly the outcomes. However, one must remember that the goal is to determine patterns and trends of the system and not values. Values do not lead to system understanding in the same manner that patterns and trends do. But increased convergence in terms of values is expected to provide sturdier ground for the evaluation of overall system behaviour.

The cost of food in the model does not capture the nature of supply and demand and associated price hikes and drops. A price that rises or falls based on the season would be a more accurate representation of the cost of food. Furthermore, separate food prices for the sale of each of the food crops would increase the accuracy of the model. In the same way, tobacco prices could be modelled as a random variable that corresponds to a particular statistical distribution to induce the price fluctuations typically seen in the tobacco industry.

Improvements outside the model scope

Labour would make a valuable inclusion to the model. However, the informal manner in which ganyu is traded makes its quantification difficult in terms of the actual cost incurred by the farmer. Also, the informal agreements that often define the terms of contract for ganyu labour are extremely difficult for the model to capture. For example, a farmer might not be able to afford the going ganyu rate (if some consensus on value could be determined), however, the labourer might agree to work for 'free' in order to receive the first cuttings at the farmer's next cassava or sweet potato harvest. Furthermore, sometimes farmers that plant different crops have peak labour demands at different times. Therefore, they agree to work for each other in a labour exchange at the time of each farmer's peak demands of labour. These social dynamics are incredibly tough to quantify, and it is quite possible they have a real impact on the dynamics of the system.

An area of further research that would prove complementary to the model is the construction of a similar model at a coarser spatial resolution but the same temporal resolution. This would be a regional level model. If this model could capture the dynamics of regional food production and the regional effects of the presence of ICs, then the impacts of ICs on food security could be better understood. This model would seek to understand the effects of infrastructure development, the hiring of local labour, white collar jobs, clinics and schools funded by IC processing companies, and increased spending on the region.

Outputs of this model, such as regional food prices, could then be used as inputs into the household level model. Together, these two models could simulate the effects of IC expansion on food security with much greater effect.

6.4 Reflection on research

A household level model was chosen as the type of model to be built because models of similar structure, and at this level of detail, that model food security and that aim to include social, economic, and physical systems, do not exist. This was the gap in the literature that was identified. It was thought that a model of this form would give a unique perspective on the food security issues facing smallholder farmers in Malawi. This belief was found to be true, however, admittedly not in the expected manner.

Ultimately, this unique perspective was largely obtained through the model building process; through asking questions, hypothesizing relationships, and learning the intricacies of the system – often uncapturable within the simulated model – all the while slowly forming a unique understanding of the impact ICs have on food security within the region. In contrast, the simulated results seemed to mostly validate that which was already known or predicted by the modeller, offering relatively few revelations.

And maybe this is the success of the SD methodology, where the process of meeting with stakeholders, building conceptual models, and translating this into the quantitative realm is where much of the learning takes place. In this sense, it is the building of the model which served as the real tool for understanding the system rather than the completed model.

In hindsight, the lack of models at this level of detail and complexity in the literature is less surprising. However, this does not mean that either the process or the model is lacking in value, rather, if the option presented itself, the author would begin modelling at the regional level and upon completion of that model progress to a model at the household level such as the one presented here.

6.5 Concluding remarks

Food security is a large and complex problem. If there is anything that is evident from this study, it is that fact that there is no single solution to the issue at hand. Rather, progress will take the form of many incremental steps by an array of stakeholders at all levels. The role industrial crops will play in this progress is unknown. However, the study concludes that ultimately the expansion of industrial crops offers benefits to smallholder farmers that otherwise would not be available. The potential for industrial crops to be used as a mechanism for positive change is there - and evidence for this both exists and is observable - the onus is on stakeholders to use this mechanism to its potential.

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Appendices

A. Sub-models

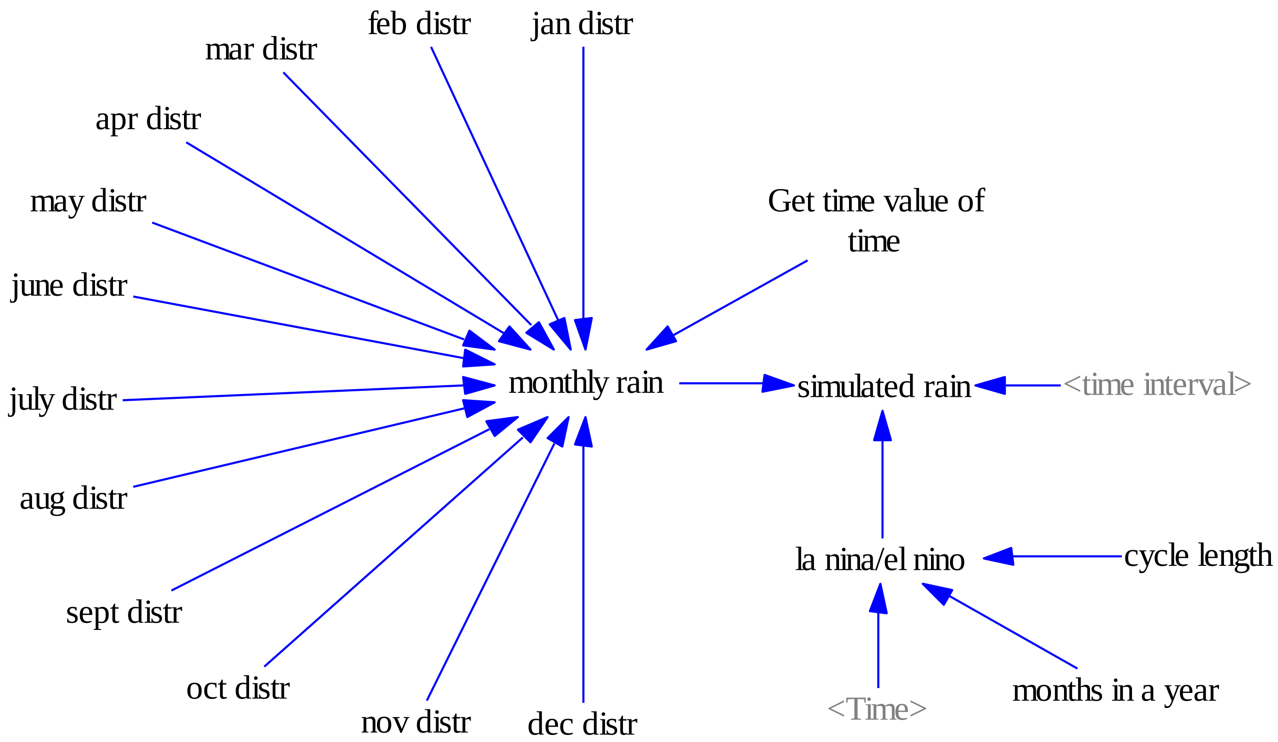


Figure A.1: Rainfall sub-model

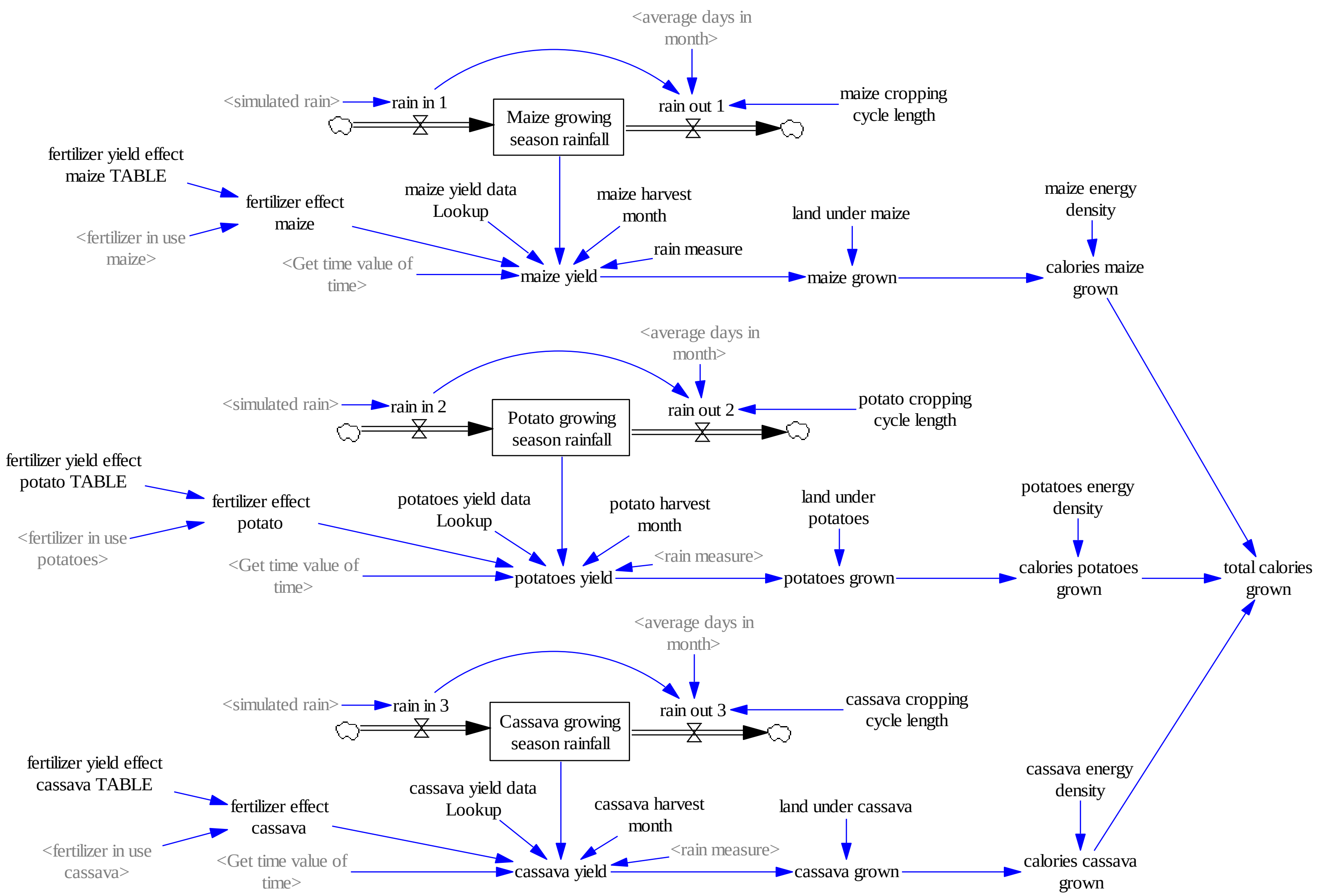


Figure A.2: Food production sub-model

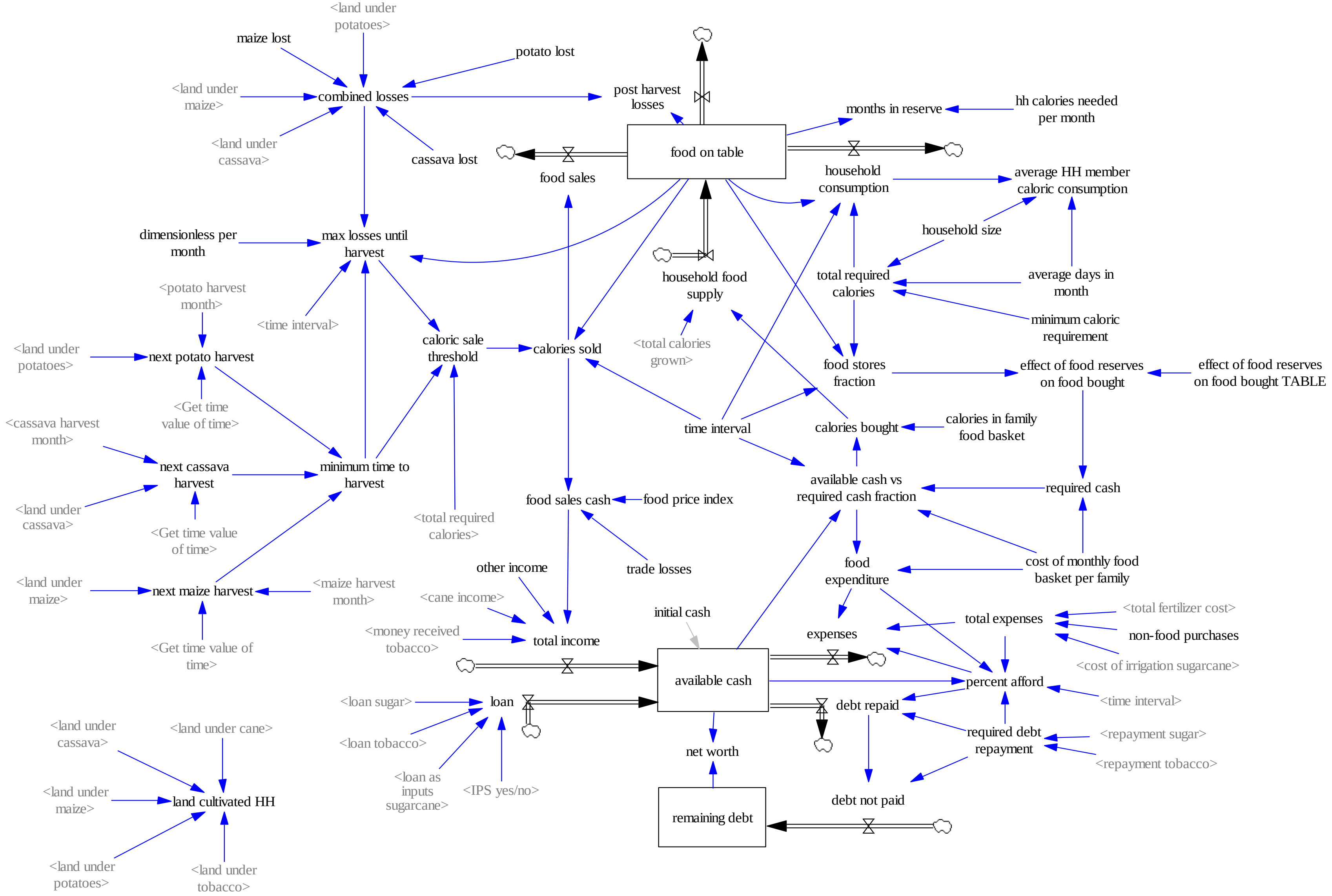


Figure A.3: Rainfall sub-model

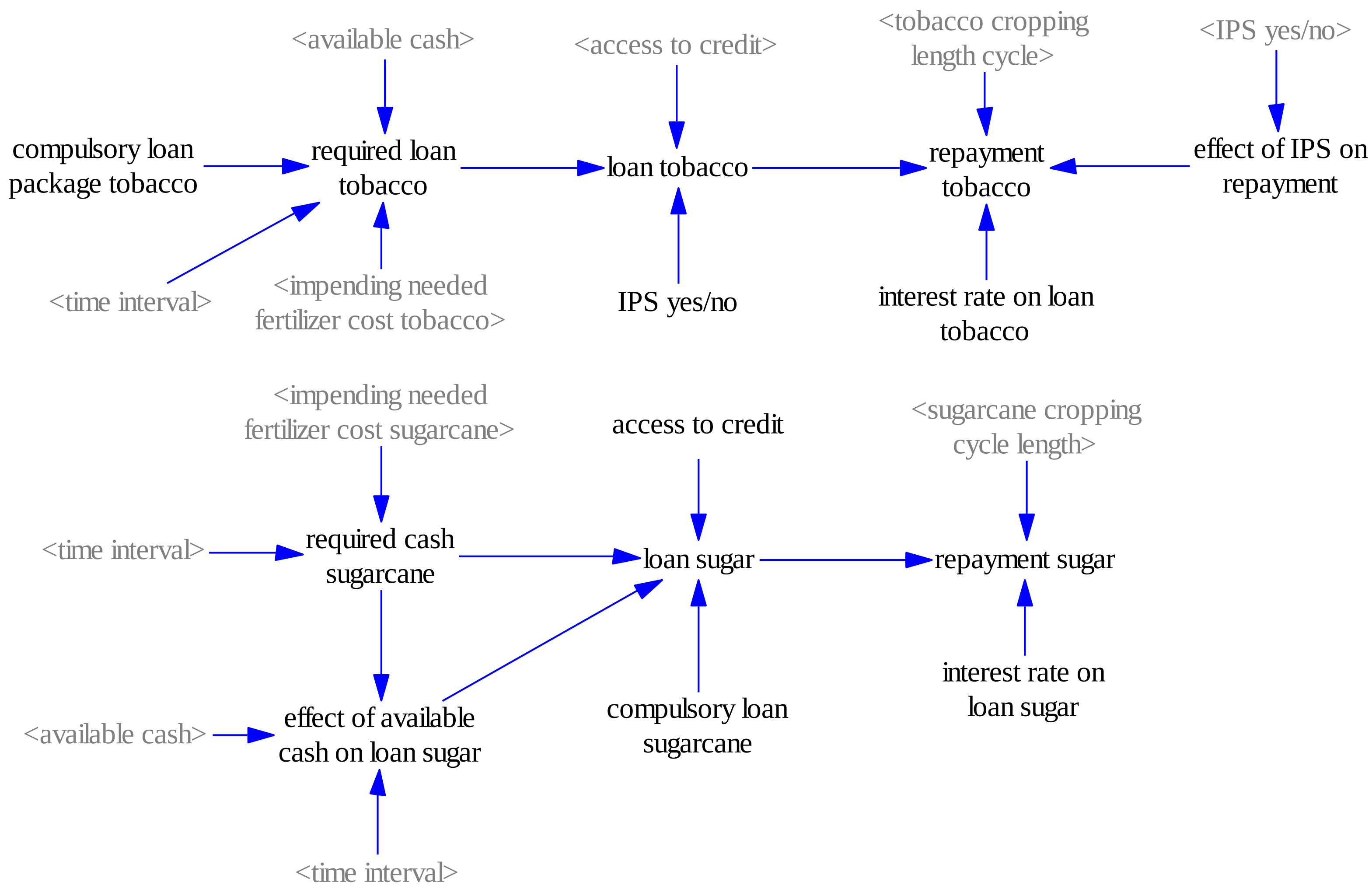


Figure A.4: Access to Credit

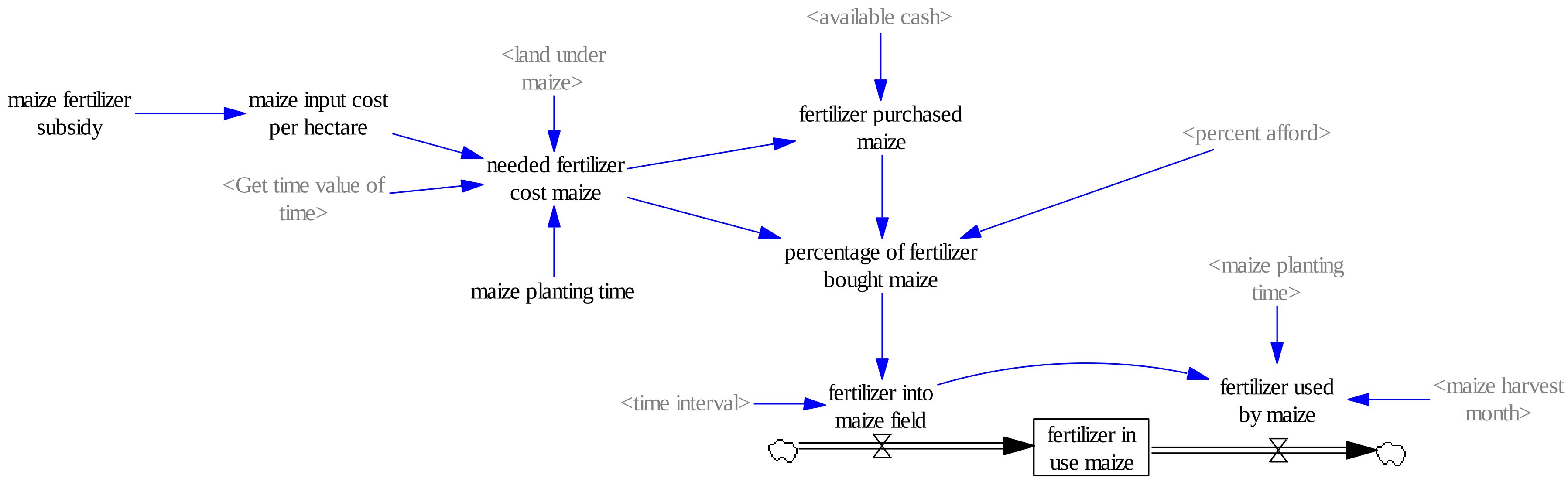


Figure A.5: Maize inputs sub-model

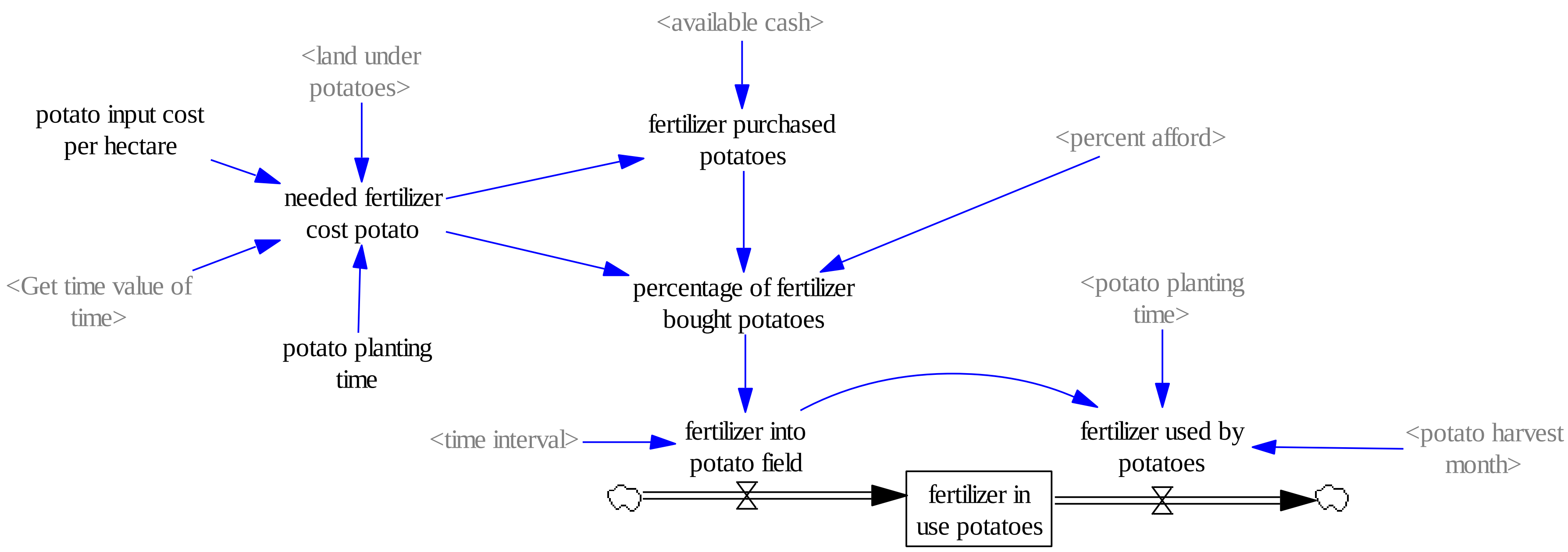


Figure A.6: Potato inputs sub-model

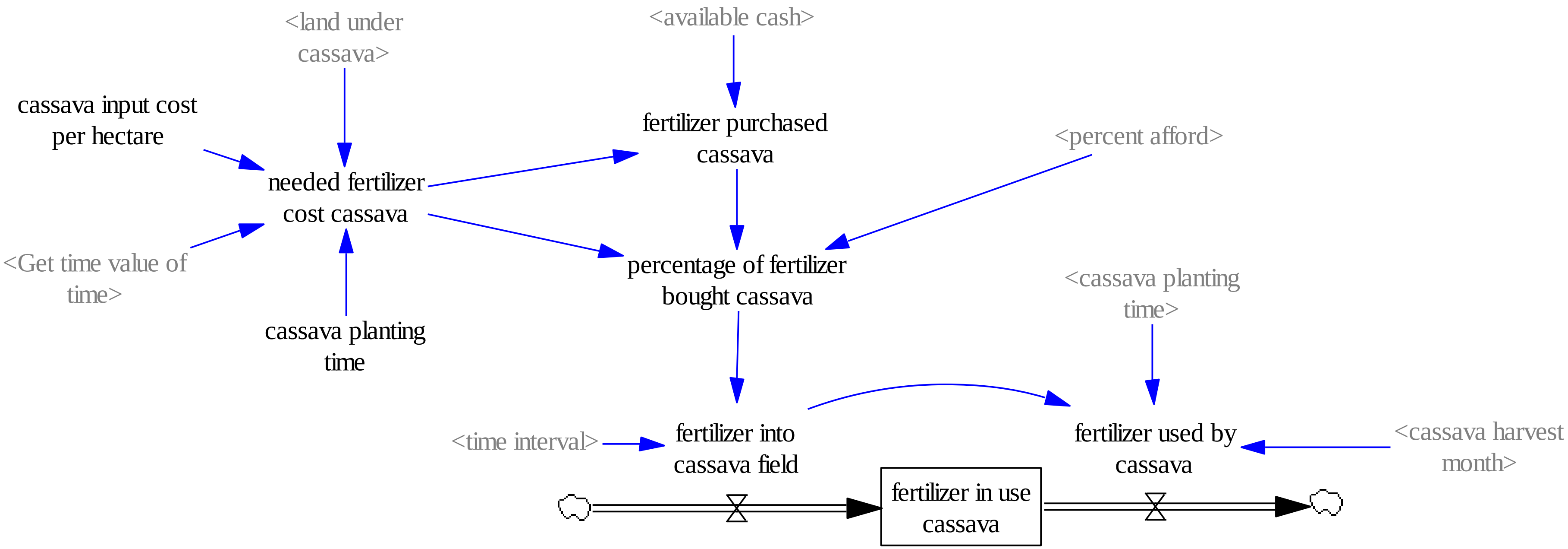


Figure A.7: Cassava inputs sub-model

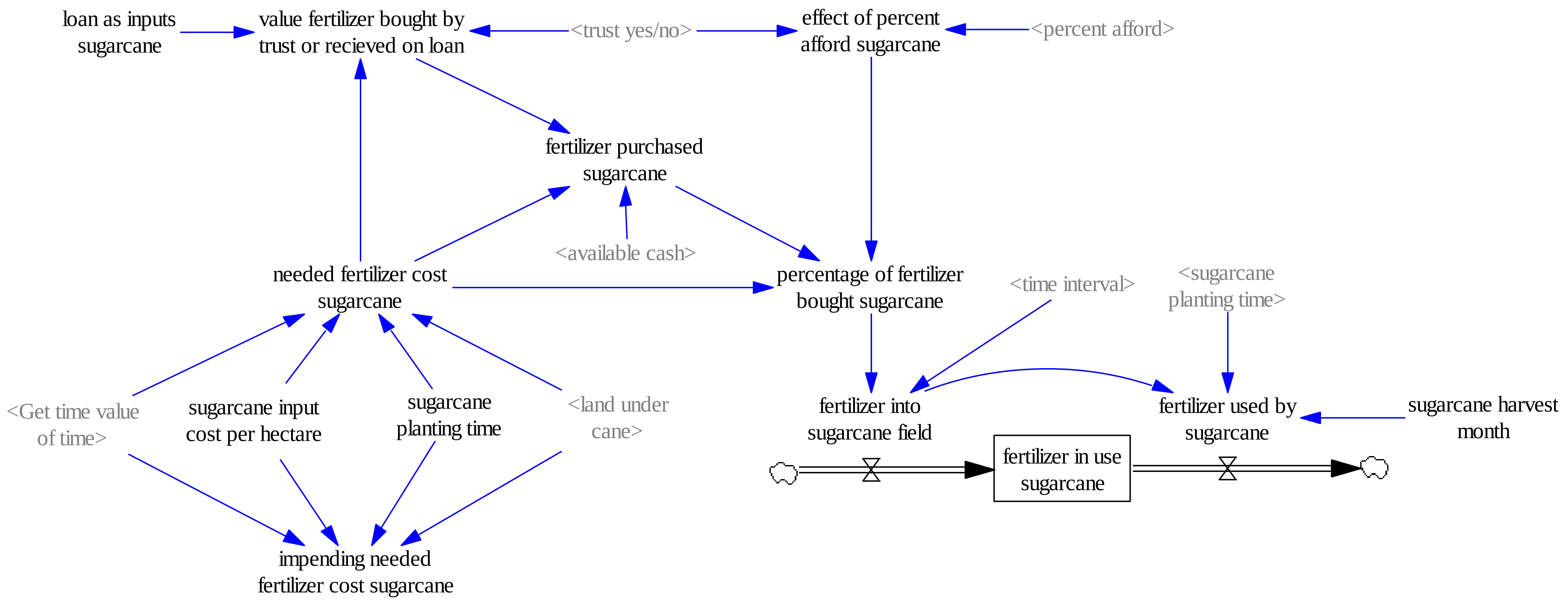


Figure A.8: Sugarcane inputs sub-model

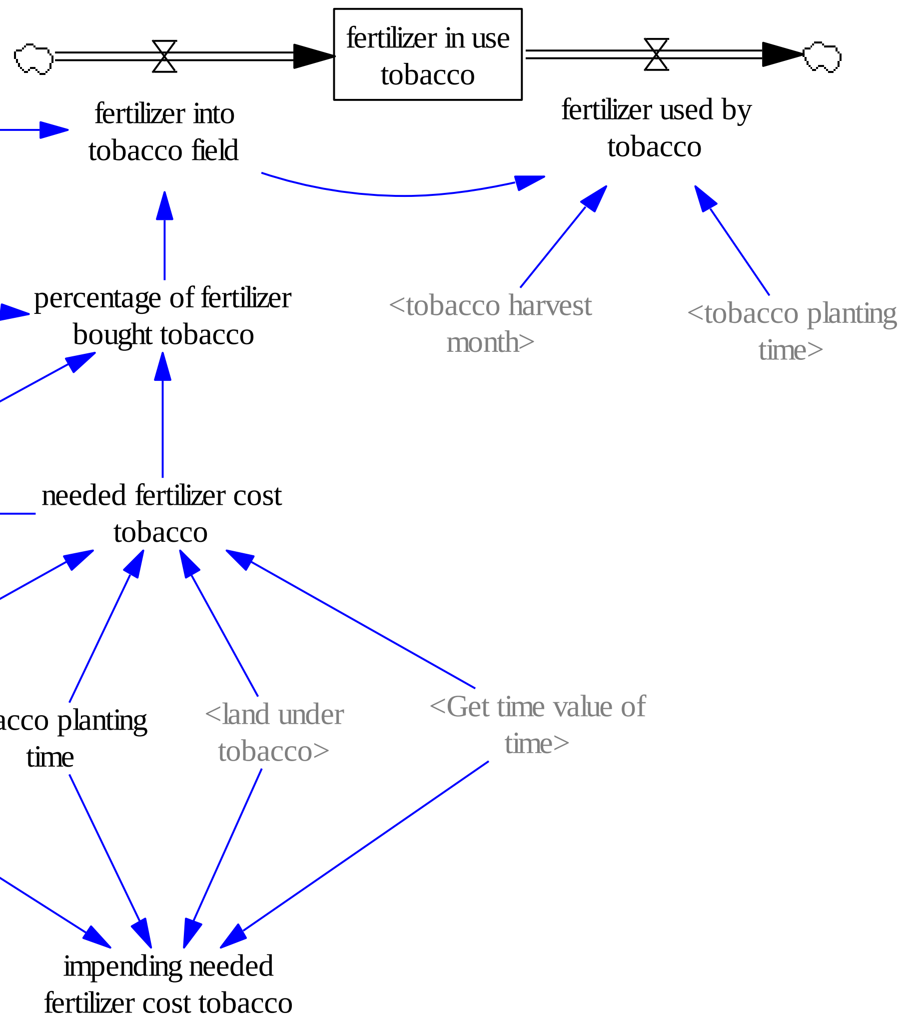


Figure A.9: Tobacco inputs sub-model

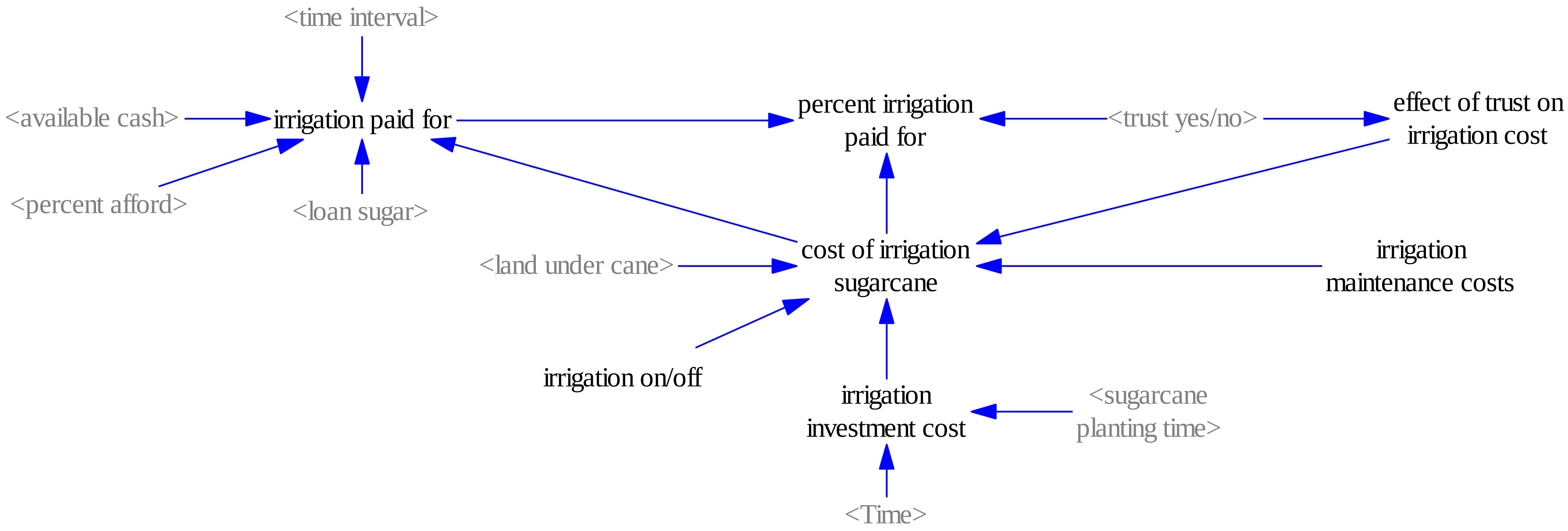
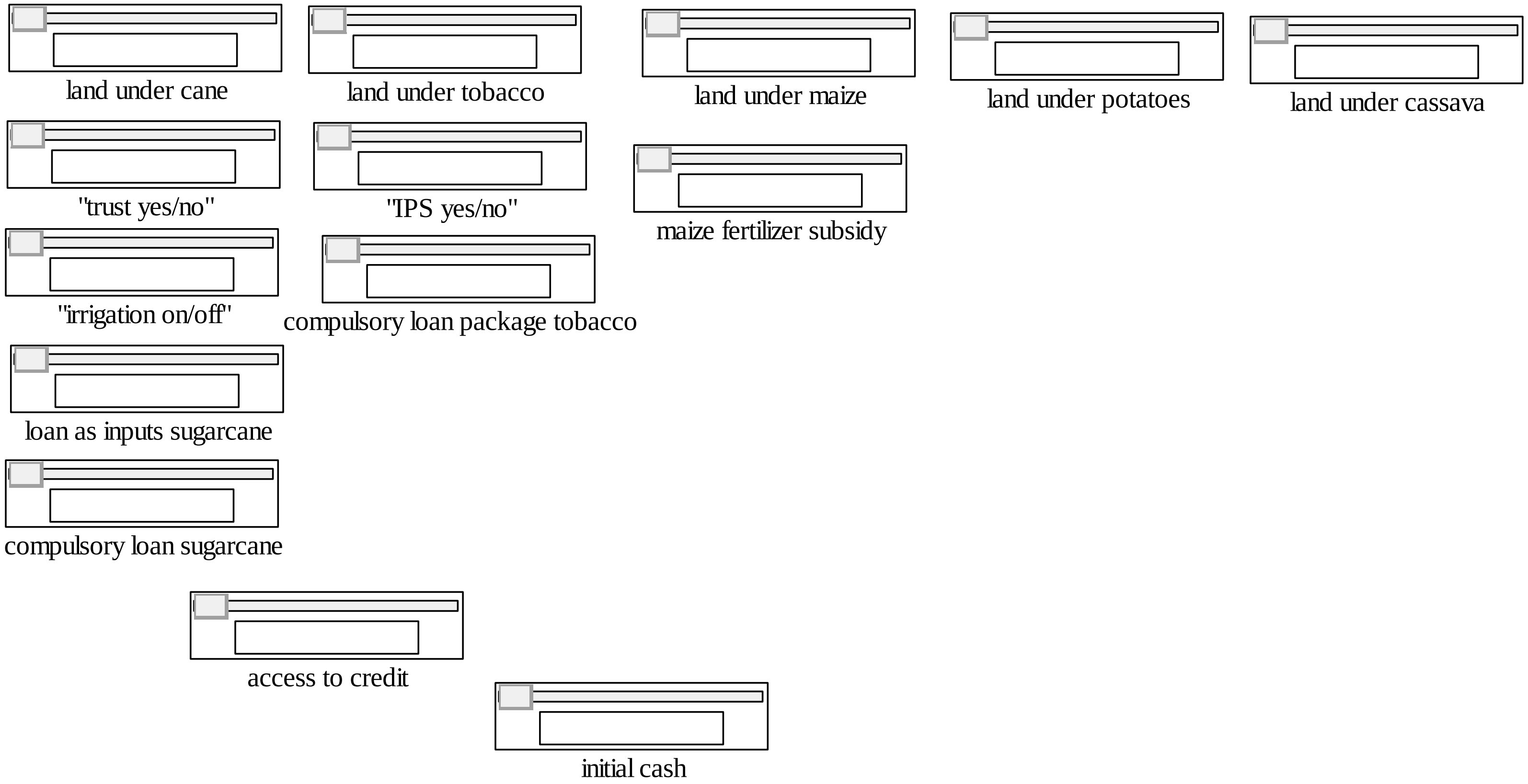
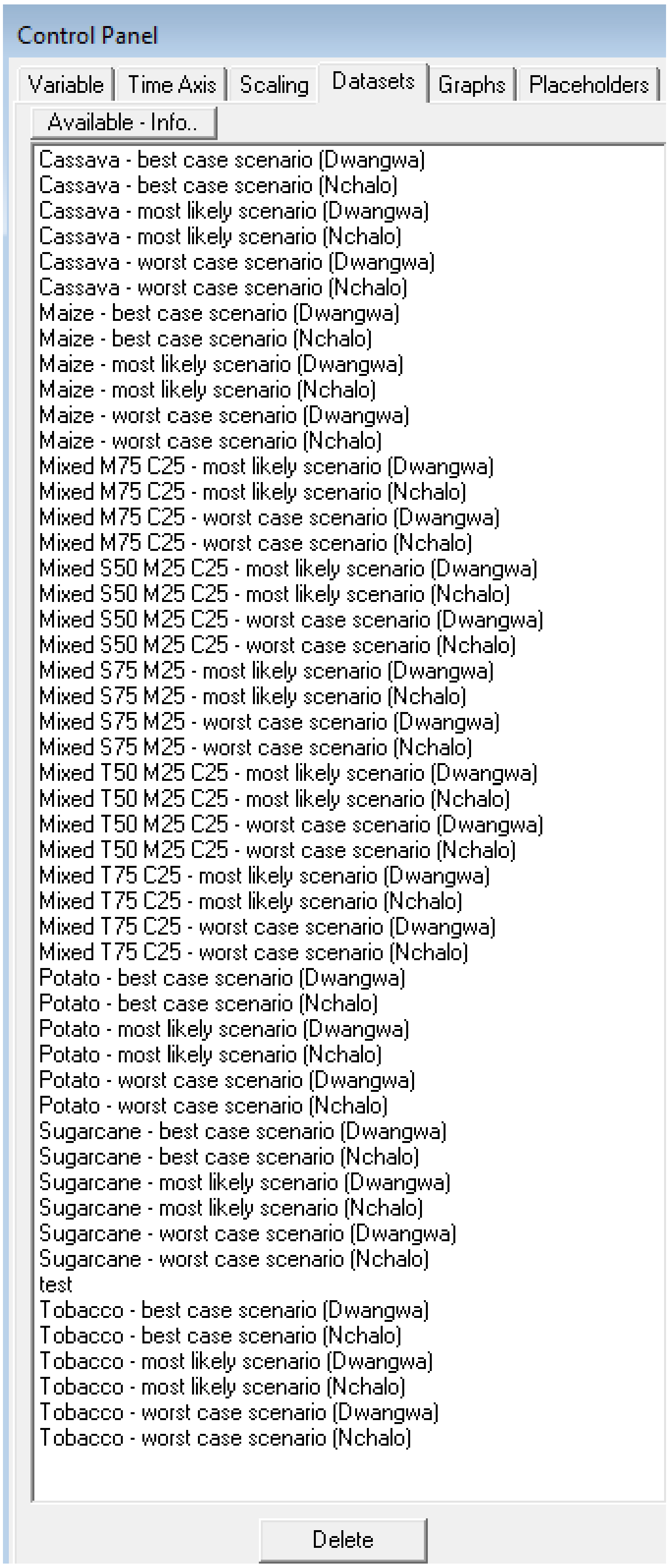


Figure A.10: Irrigation sub-model

B. Decision variables



C. Simulation-runs



D. Causal Loop Diagrams

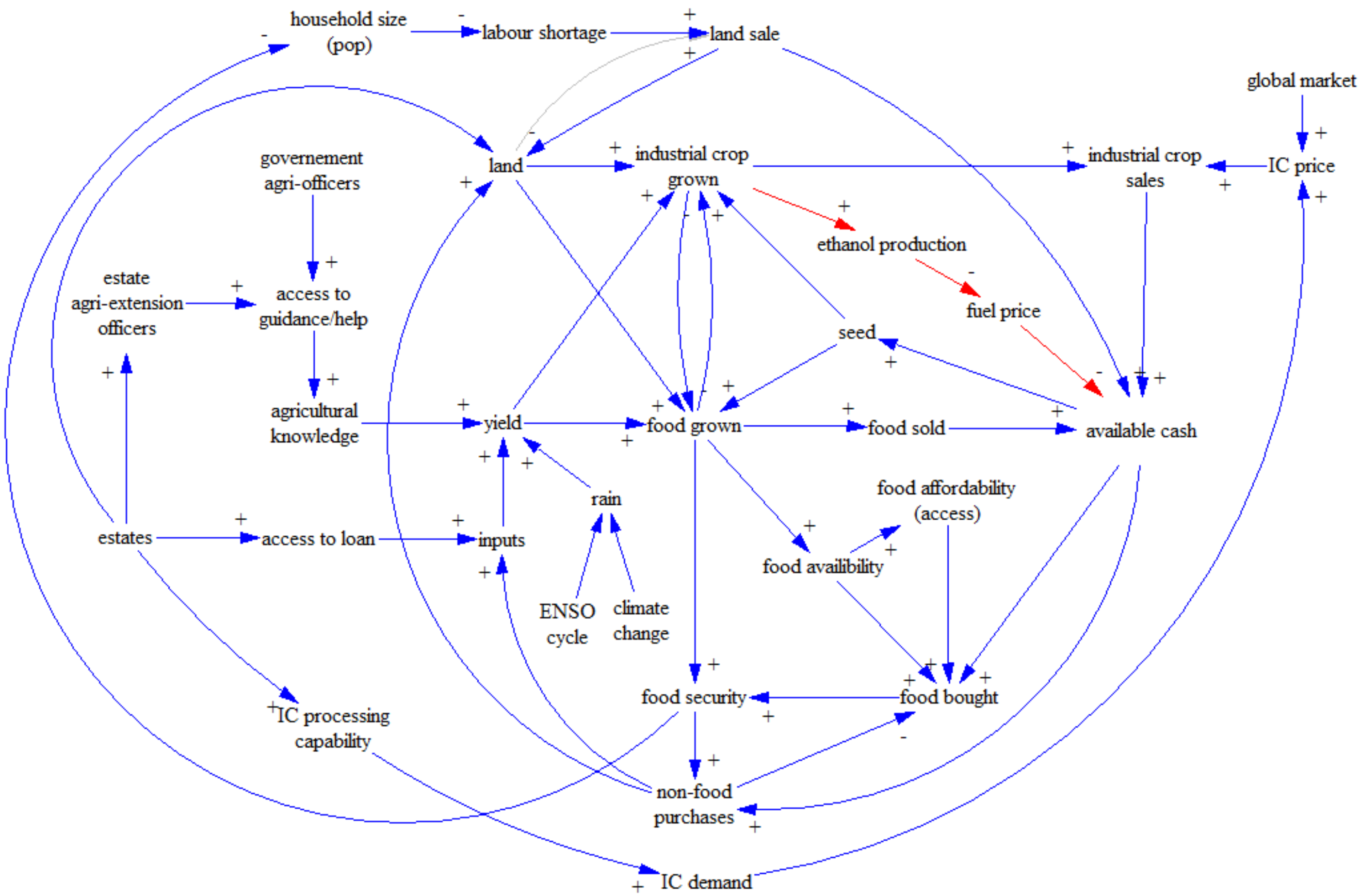


Figure D.1: Causal loop detailed

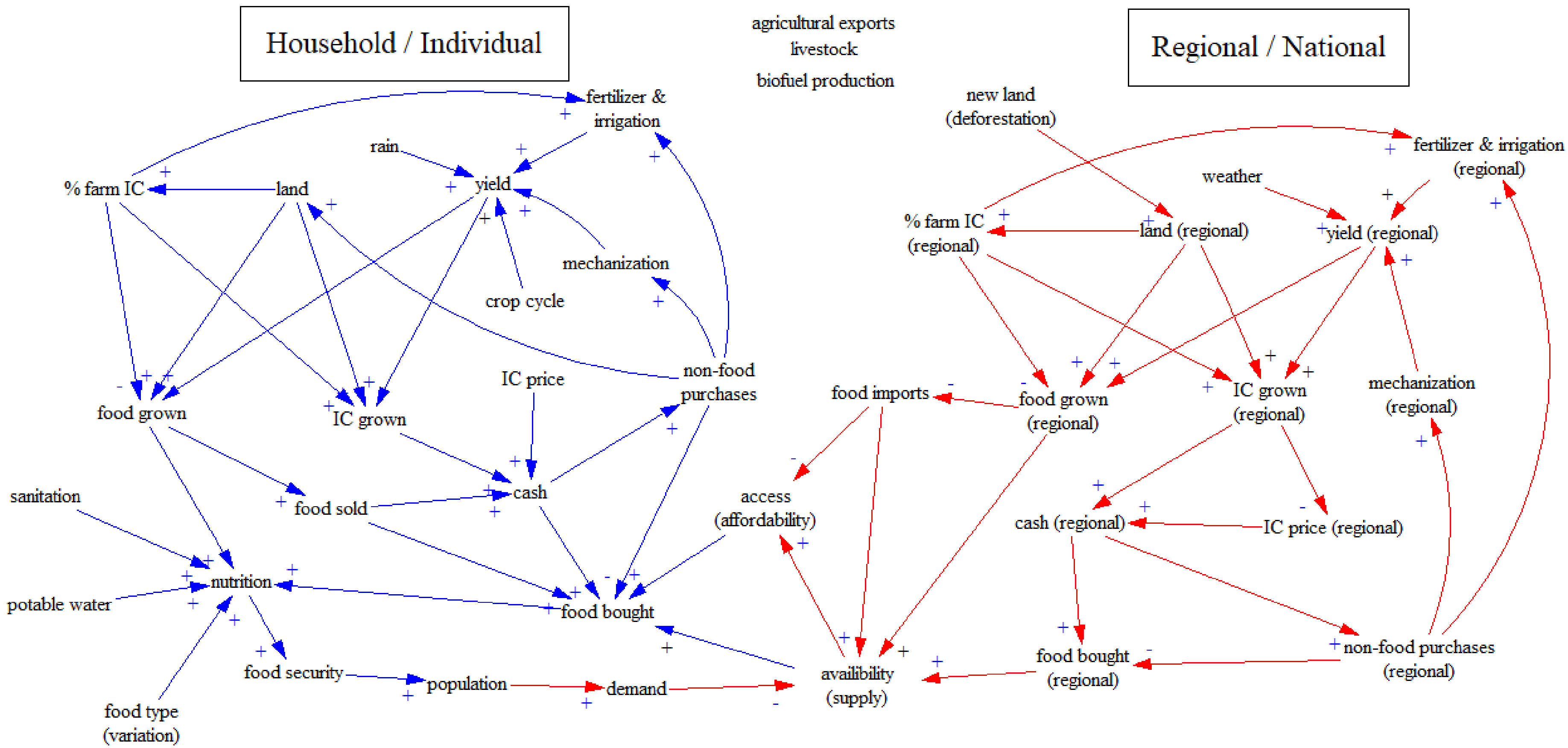


***Figure D.2**: Causal loop regional and household*