Impacts of Industrial crops on food security in Swaziland, Tshaneni: A system dynamics approach

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Declaration

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Abstract

Impacts of industrial crops on food security in Swaziland, Tshaneni: A system dynamics modelling approach

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Tshaneni, Swaziland has seen a prolific expansion in the cultivation of industrial crops over the last two decades. The effect of these industrial crops on local and regional food security is unclear. This is because there are multiple drivers of food security in the region. Drivers of food security span the economic, social, and agronomic sector and the interactions within, and between, these sectors mean that the food security system is complex. To explore the effect of industrial crops on food security the systems thinking approach is used to aid in system understanding. The aim of this study is to use systems thinking to analyse the food security system in Tshaneni Swaziland, to build a conceptual model of the system using causal loop diagrams, and to build a fully executional computer-based simulation to model the system quantitatively.

A review of the literature revealed system dynamics as the most suitable modelling methodology for this study. The model consists of six sub-models that represent the real system. The sub-models include economic, production, and consumption feedbacks at the household level, where both food crop and industrial crop cultivation is simulated. The model is driven by a combination of external drivers, such as environmental conditions, and internal drivers, such as human decisions. The amount of money and food (in calories) available to the household are used as the food security indicators. The model is run for five different scenarios covering a twenty-year period from 2016 to 2035. These are analysed in order to determine the impact of industrial crops, in this case sugarcane, on food security.

Results show that household involvement in sugarcane leads to increased levels of food security, mainly because of an increase in money available and irrigation for food crop production. Education and occupation were additional factors found to play a major role in increasing food security. Scenarios that explored the impact of climate change and potential water scarcity revealed that households in Tshaneni, Swaziland remain vulnerable to drought in terms of food security. However, those households involved in industrial crop cultivation are less vulnerable to climatic conditions than households that farm only food crops. This is because cultivating industrial crops leads to increased access to irrigation, which is also used for small plots of food crops. Based on the findings of this research project, it is advocated that smallholder farmers engage in the cultivation of sugarcane, especially in the context of large state-supported projects that have significant private sector buy-in, such as that in Tshaneni. The study further provides recommendations to stakeholders and policymakers to continue to invest in the sugar cane industry to ensure a food secure future for Swaziland and its people. Benefits of system dynamics are provided and recommendations are made to future researchers attempting to improve this research.

Uittreksel

Impak van industrieële gewasse op voedselsekerheid vir Swaziland, Tshaneni: Stelsels dinamika benadering

("Impacts of industrial crops on food security in Swaziland, Tshaneni: A system dynamics modelling approach")

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Tshaneni, Swaziland het oor die laaste twee dekades vreeslik baie industrieële gewas uitbreiding gesien. Die impak wat uitbreidings soos hierdie op voedselsekerheid het in hierdie konteks is onbekend as gevolg van sisteem kompleksiteit. Industrieë gewasse het baie positiewe (mense verdien meer geld) en negatiewe (mense plant nie meer so baie voedsel gewasse nie) gevolge en daarom is die antwoord nie so vanselfsprekend nie. Om hierdie effek van industrieële gewasse op voedselsekerheid te verstaan word daar van 'n stelsels denkwyse gebruik gemaak. 'n Spesifieke modellerings metode moet geïdentifiseer word, genoeg kennis moet opgedoen word om 'n uitgebreide model te bou en die invloed wat partye op mekaar in die sisteem het moet ten volle verstaan word. Die doel van hierdie studie is om stelsels denkwyse te gebruik om voedselsekerheid in Tshaneni Swaziland te analiseer deur 'n konseptuele model asook 'n rekenaar simulasie model van die sisteem te bou.

Na die bestudering van literatuur, was stelsels dinamika geïdentifiseer as die verlangde modellerings metode en die model was gebou. Die model bestaan uit ses sub-modelle wat die werklike sisteem simuleer vanaf 2016 tot en met 2035. Die sub-modelle sluit ekonomiese, produksie en verbruiks modelle op huishoudelike vlak in. Voedsel gewas en industrieële gewas produksie is gemodelleer. Die model word deur beide omgewings en mense besluitneemings faktore beïnvloed. Voedselsekerheid word deur die vier pilare beskryf wat gedefineer is deur die "FAO". Hierdie sluit in toegang, beskikbaarheid, stabiliteit en benutting van voedsel. Twee veranderlikes naamlik "*Money available*" en "*Calories available*" word gebruik om 'n huishouding se voedselsekerheid aan te dui. "*Money available*" verteenwoordig voedsel toegang en stabiliteit terwyl "*Calories available*" voedsel beskikbaarheid en stabiliteit verteenwoordig. Vyf verskillende scenario's word gebruik om die vraag rakende die impak van industrieële gewasse op voedselsekerheid te antwoord, maar elk vanuit 'n ander perspektief.

Die model resultate bewys dat betrokkenheid, op enige manier by industrieële gewas uitbreiding, lei tot beter voedselsekerheid as gevolg van besproeings moontlikhede en hoër inkomstes. Daar was gevind dat opvoeding en beroep keuses twee adisionele veranderlikes is wat ‘n belangrike rol speel om voedselsekerheid te verseker. Bykomend word daar bewys deur ‘n scenario wat die impakte van klimaats verandering op voedselsekerheid toets, dat die mense van Tshaneni Swaziland, baie kwesbaar is teenoor droogte. Huishouding tipes word gerangskik volgens voedselsekerheid’s vlak. Die beste en slegste huishoudelike samestellings word ook gelys in terme van voedselsekerheid. Die studie verskaf verder voorstelle aan belanghebbendes en beleidmakers om aan te hou belê in die suiker industrie om ‘n voedselseker toekoms vir Swaziland en sy mense te verseker. Sekere model tekortkominge word beskryf en verduidelik. Daar word uitgebrei oor die voordele van stelsels dinamika en voorstelle word gemaak aan toekomstige navorsers wat dieselfde navorsingsveld wil betree.

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To my brother and his wife, thank you for all the encouragement and phone calls.

Lastly to God for His never-failing grace, love and strength that I receive.

Dedications

I would like to dedicate this thesis to my brother, Sybrand Abraham Engelbrecht who passed away in 2014. Thank you for all the valuable life lessons I could learn from you. You really helped me to know who I am and what I want to do with my life. Thank you that you always believed in me and encouraged me to follow my dreams.

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List of Acronyms

SSA	sub-Sahara Africa
ICs	Industrial Crops
FAO	Food and Agricultural Organization of the United Nations
FICESSA	Food security impacts of industrial crop expansion in sub-Saharan Africa
GDP	gross domestic product
SWADE	Swaziland Water and Agricultural Development Enterprise
KDDP	Komati Downstream Development Project
RSSC	Royal Swazi Sugar Corporation
SNL	Swazi National Lands
TDL	Title Deed Land
GE	Genetic engineering
SKPE	Swaziland Komati Project Enterprise
FAs	Farmers Associations
NMs	Network models
SDM	System dynamics modelling
MIT	Massachusetts Institute of Technology
DES	Discrete event simulation
ABM	Agent-based modelling
CLD	Causal loop diagram
SFD	Stock and Flow Diagram
R	Reinforcing loop
B	Balancing loop

Chapter 1 : Background

1.1 Introduction

There is an increasing trend to allocate land in sub-Sahara Africa (SSA) for the production of (industrial) crops that are ultimately used for non-food purposes such as bioenergy, fibre and other industrial processes (Belmont Forum and FACCE-JPI, 2013). Land conversions like these are often financed through direct foreign investment and are justified as an engine of economic growth. However, in most of the countries where this take place, food security is a real concern and therefore raises questions with regards to the impact that these land conversions have on food security (Belmont Forum and FACCE-JPI, 2013).

It is well accepted that industrial crops (ICs) compete directly and indirectly for land with food production, but it is not always straightforward to assess the overall impacts of this competition on food security. Superficially food security should decrease as agricultural land is converted to ICs. Yet there are a number of less obvious mechanisms that may lead to improvements in food security like higher household incomes that can improve access to food or access to fertilizers/pesticides that leads to improved food crop yields (Belmont Forum and FACCE-JPI, 2013).

One of the SSA countries where land conversions took place is Swaziland, more specifically on the northern border of the Hhohho and Lubombo provinces, near the town of Tshaneni, which is situated in the north-eastern corner of Swaziland as shown in Figure 1-1.

Figure 1-1: Map of Swaziland

The Tshaneni area is considered lowveld and the vegetation is classified as Lowveld savanna or more specifically microphyllous (Acacia) savanna (Monadjem, 2005). The area is at altitudes between 150m to 400m above sea level and is separated from the Mozambique coastal plains by the Lebombo mountain range. Mean annual rainfall ranges from 550mm to 725mm and the mean monthly temperature in January is 26ºC and 18ºC in July (Monadjem, 2005).

1.2 The broader picture

The continent of Africa is going to face a major problem in the 21st century, namely: how to feed the rapidly growing population of the continent. How Africa adapts to climate change will also play a big part on the food security of the continent (Seiler, 2013) as Oseni & Masarirambi (2011) proved that climate change has affected the overall maize yields negatively in sub-Saharan Africa countries like Swaziland over the past 20 years.

The term food security was introduced at the World Food Conference in 1974 that was held in response to the food crises and major famines in the world. This term was taken up and developed, evolved and diversified by the academic community and politicians. Up to two hundred definitions have been deployed for this term from then, considering it from original viewpoints (Smith, et al., 1992).

The definition emerging from the World Food Summit held in Rome in 1996 was that: "*There is food security when all people at all times have sufficient physical and economic access to safe and nutritious food to meet their dietary needs including food preferences, in order to live a healthy and active life*". Whenever any individual or population lacks this or might be vulnerable due to the absence of one of the above-mentioned factors then it is at risk or suffers from food insecurity (FAO, 1996) & (Giraldo, et al., 2008).

The food security of a country has a very high level of complexity due to; the lack of tools or methodologies capable of assessing the effects of long-term policies in the system; actors acting under pressure and therefore failing to play their proper expected roles and the lack of a holistic system model to facilitate intervention and understanding of the system (Saeed, 1994). Some other factors also include contextual factors of countries such as the weather patterns; the socio-economic, political and environmental development and health sector practices.

1.2.1 Study background and origin

Africa's population is growing rapidly and it is expected that it will double from 1 billion in 2010 to almost 2 billion in 2050. In the same context, from the year 2000 to 2050 eight of the top ten countries regarding highest average annual growth rate in the world are African. In addition, until 2055, 18 out of the 20 countries with the highest population growth rate are located in sub-Saharan Africa (United nations, 2003). Therefore it is clear that many people will need food in the near future of Africa and more specifically sub-Saharan Africa. This rapid growth puts a lot of stress on countries in order to stay food secure.

There are two ways to ensure food security for these countries, namely importing food from other countries or by self-producing the crops. There are a few problems regarding importing food from other countries. The problems include that food could be more expensive because of transportation and other costs, it also has no benefit to the country in terms of job creation and can undercut local farmers and have devastating impacts on local industries. The countries' (currently exporting food) population will also increase in the coming 50 years and therefore they will use more of their own produce in the future. Leaving countries that were dependant on imports in a food insecure position (Seiler, 2013). This creates a dilemma as it implies (in the long term) that countries (reliant on food imports) should produce more food with a limited amount of arable land.

According to *Belmont Forum & FACCE-JPI (2103),* the recent trend in sub-Saharan Africa is to allocate (or expand) land that was previously used to grow food crops, for the production of industrial crops (ICs) such as sugarcane, jatropha, tobacco and cotton. The competition between food crops and ICs has been a contentious issue in the academic and policy fields. Some studies suggest that the eventual food security outcomes of IC expansion can be positive (Reddy, et al., 2008) & (Brittaine & Lutaladio, 2010) and others suggest that it will be negative (Tenenbaum, 2008) & (Elobeid & Hart, 2007). As in all competition-related debates, there are many factors that will influence the outcome. Subsequently there is currently no clear indication of what influence these IC crop expansions will have on food security in the long run (Belmont Forum and FACCE-JPI, 2013).

Therefore a gap exists in the understanding of the influence of the impact of ICs. It also has a wider impact than just food security, like life quality and socio-economic impacts just to mention a few.

Professor Alexandros Gasparatos from the University of Tokyo identified this gap and proposed a project to the International Opportunities Fund. The project was approved and the title leads as follow: Food security impacts of industrial crop expansion in sub-Saharan Africa (FICESSA). This project looks at the whole system from the different plant species to the economic side as well as the modelling side and includes a few sub-Saharan African countries of which Swaziland is one.

This project is a component of the bigger international project and will focus on only modelling the system and only for Swaziland. All the information needed to build the model will be gathered by groups of people doing fieldwork for the FICESSA project (Belmont Forum and FACCE-JPI, 2013).

1.3 Overview of Swaziland

Swaziland is one of Africa's smallest countries and is completely landlocked by South Africa and Mozambique. Most of the people (about 1.3 million) in Swaziland lives in rural areas (75% of the population), but because of its size, people are never too far away from urban areas. The country's economy stagnation in the last few years led to high poverty and unemployment rates. About 45% of Swaziland's population is considered poor and live from less than US$1 per day (Tevera, et al., 2012).

This overview will provide background on Swaziland's agriculture sector as well as elaborate on one specific project that is running in the Tshaneni area as explained in the introduction. Finally, this section explains the current state of food security in Swaziland and projects contributing to that.

1.3.1 A short overview of Swaziland's agriculture

The agriculture sector is the second largest contributor to the economy in Swaziland after the manufacturing sector. In Swaziland, there are two main types of farming sectors, the commercial sector and subsistence farmers. The commercial sector's main production commodities include sugar, canned fruit and beef for export. Subsistence farmers mainly grow maize. Much of the country's demand for agricultural products is met through imports from South Africa (Central Bank of Swaziland, 2015) & (US Embassies abroad, 2016).

According to Dlamini, et al. (2016) the sugar industry makes up 18% of the total gross domestic product (GDP), which is a significant portion for a single agricultural sector. This is also 59% of the agricultural sector by value. Beef as a commodity makes up another 14 % of the gross agriculture value. The smallholder/subsistence farmers constitute 70% of the population and occupy 75% of the cropland, but are not very productive as they are accountable for only 11% of agricultural outputs (Sikuka & Torry, 2016). Therefore people are under lots of pressure and struggle to stay food secure.

Swaziland is divided into four climatic regions, namely the highveld, the middleveld, the lowveld and the Lubombo plateau as shown in Table 1-1. (ProBEC Biofuels Newsletter, 2007). The rainfall ranges for these four regions shown in Table 1-1. Table 1-1 additionally shows that the precipitation in the Lowveld region (which includes the Tshaneni area) is the lowest of all the regions. Therefore, crop farming in this region is dependent on irrigation and without it expansion possibilities are limited. Figure 1-2 indicates the climatic regions as indicated in Table 1-1.

Table 1-1: Rainfall in climatic regions, adapted from (FAO aquastat, 2005)

Climatic region	Rainfall (mm/year)
Highveld	700 – 1550
Middleveld	550 – 850
Lowveld	400 – 550
Lubombo Plateau	550 – 850

Therefore, the Swaziland government introduced a few projects that are run by the Swaziland Water and Agricultural Development Enterprise (SWADE). One of these projects is the Komati Downstream Development Project (KDDP).

Figure 1-2: Climatic regions of Swaziland (ProBEC Biofuels Newsletter, 2007)

1.3.2 Overview of the Komati Downstream Development Project (KDDP)

The Maguga dam project was established in 1992 under the *Komati Basin Treaty* between Swaziland and South Africa (FAO aquastat, 2005). By the year 2001 construction of the 332 million cubic meter dam was completed and it was opened. The KDDP commenced in July 1999 when smallholder farmers downstream of the dam (Tshaneni area) started to develop their land into irrigated farms for commercial agriculture. It is important to note that this was the first time irrigation came to this specific area. As mentioned above, the project is run and overseen by SWADE and it aims at utilising Swaziland's full 83 million cubic meters portion whilst improving the standard of living for the communities involved (SWADE, 2017).

The KDDP's main focus is to assist farmer companies in the project development area to establish and operate irrigated farms which cover 6000ha. To this day a total of 5206ha has been developed of which 4616ha is under sugarcane (target was 4500ha) and the remaining 590ha is used to produce food crops. In addition to this 2360 homesteads have irrigated home gardens where vegetables are grown. This adds 205ha of land where vegetables are planted (SWADE, 2017).

The project brought lots of opportunities to the Tshaneni community, but are also dominated by sugar production, which is an IC and therefore raises questions regarding food security. The next section gives an overview of current food security projects in Swaziland.

1.3.3 Current state of donor funding helping Food Security in Swaziland

In the past, there have been many projects in Swaziland assisting people to be food secure. To this day there are still many that provide to the people in need, of Swaziland. Most of these projects are internationally funded through organisations like the Japan International Cooperation System (JICS) (Japan International Cooperation System, 2009), the United Nations (UN) through a program called the International Fund for Agricultural Development (IFAD) (Office of the Secretary-General's Envoy on Youth - UN, 2016) and the World Food Programme (WFP) (World Food Programme, 2017).

The JICS had a project in Swaziland back in 2008 called *Grant Assistance for the Food Security Project for Underprivileged Farmers (FY2005)* where they gave a grant of 109 million yen to support underprivileged farmers through procuring tractors and operating machines (Japan International Cooperation System, 2009). The IFAD managed by the UN currently has a project in Swaziland with a total project investment of $21.1 million. These funds include contributions from different sectors and countries. The aim of this project is to finance the Smallholder Market-led Project (SMLP), an initiative that will improve food and nutrition security as well as incomes of about 10900 households in the Lubombo and Shiselweni regions in Swaziland (Office of the Secretary-General's Envoy on Youth - UN, 2016). Contributions from the WFP to Swaziland have been going on for many years, but recently they have been assisting 250 000 people affected by the recent El Nino through unconditional cash transfers (World Food Programme, 2017).

1.4 Problem Statement

In Swaziland, there is a debate regarding whether the KDDP that is managed by SWADE (explained in section **1.3.2**) has a positive or negative influence on the food security of the involved community (or the country). As the years go by, more land in that area is used to rather plant sugarcane than for its previous purposes that included maize planting and cattle grazing areas. This is done since the sugarcane farmers do better financially. Therefore speculation exists as to whether less food is being produced in that area now than before and if so, did that result in higher food prices and people being worse off than before? Thus the two main concerns are whether it is sustainable and whether farmers are really more food secure because of higher incomes or is it just balanced out by higher food prices? In addition, the question lies as to whether the people's living standards have increased since the beginning of the project. The model that was developed through this research effort aimed to answer these questions and give insights into new policies to try and ensure food security.

1.5 Research objectives

The main objective of the study can be divided into smaller objectives that have to be reached in order to reach the main objective of answering the above questions.

The main research objective of this research project is to develop a systems-based model to understand the feedbacks between IC expansion and local food security and use it to clarify such feedbacks. More specifically this systems-based model needs to include the positive and negative feedbacks between IC expansion, land use change and local food security (Belmont Forum and FACCE-JPI, 2013). The importance of this is explained in section **1.5.2**.

The following objectives were identified in order to reach the main objective:

- Identify drivers, constraints and impacts of industrial crops on food security.
- Build a comprehensive simulation model and interpret results.
- Make recommendations (to stakeholders) to guide strategic decision making and intervention strategies for the way forward for industrial crops in Swaziland.
- Conclude on the usefulness of the method used to inform strategy and decision making.

1.5.1 Research strategy

The research strategy describes how the objectives will be achieved. The steps are listed below.

- Clearly defining food security and what it means in the Swaziland context.
- Gain a full understanding of how a simulation program works and is used to model real-life cases.

- Consult local stakeholders (through field work) to understand local dynamic feedback mechanisms that should be incorporated in the model
- Draw up influence diagrams in order to better understand the interaction between each individual role player.
- Develop a model that is universal and easy to interpret.
- Calibrate the model.
- Do sensitivity analysis on the model built.
- Use model to investigate different scenarios.
- Give interpretations of the model to stakeholders which will include personnel from the sugar industry, SWADE, government and any other interested parties.

The end result of this project will be a systems-based model that clearly explains the influence of IC expansions on local and national food security. The model should be adaptable and different scenarios should easily be simulated by the model. The model will help policy makers introduce measures to help ensure food security, help stakeholders understand the interactions between ICs and food security and with a few other knowledge gaps that are explained in the next section.

1.5.2 Importance of the research problem

According to Belmont Forum and FACCE-JPL (2013), the vision for this project is to provide knowledge to support the development of evidence-based policies as well as practical solutions that can catalyse positive food security outcomes from ICs expansion in Swaziland. The research will address knowledge gaps regarding the long-term direct and indirect influence of ICs on food security of the Swaziland people. This includes the links between the land use change effects of food-ICs competition and food security.

The research aims to provide robust, generalizable and transferable results that will be useful to the low- and middle-income economies targeted in this project. The local case study is also situated in an area that is highly food “insecure” and where the results generated from this project has the potential to produce advice that can be of high importance (Belmont Forum and FACCE-JPI, 2013).

The results will be especially of importance to the following identified end-users/stakeholders:

- **Policy-makers**: This refers to policy-makers regarding the biofuel industry in general, as ICs are in many cases grown for this purpose.
- **Policy-makers in Swaziland:** Governmental ministries including agricultural and economic ministries, who develop policies regarding the country’s agriculture and food security, as well as economic policies.

- **Private sector:** Royal Swazi Sugar Corporation (RSSC) is a private company who will be paying close attention to the results of this project. Even though SWADE is not a private company, it will still benefit in the same way the private sector does.
- **Certification bodies:** There are two international partners with whom there will closely be worked with regarding industrial crop certification. The Roundtable on Sustainable Biomaterials (RSB) and Bonsucro (BSI) have developed certification schemes that aim to enhance the sustainability of IC production.
- **Civil society:** The project has partnered with Solidaridad Southern Africa who has a proven record of influencing sustainable development at the IC crop level.
- **International organizations and science-policy interface:** This includes the United Nations system (UNU) and all their international linking partners like the Food and Agriculture Organisation (FAO) (Belmont Forum and FACCE-JPI, 2013).
- **Members involved in the KDDP:** All members directly and indirectly involved with the project.

1.6 Ethical implications of the research

Ethical approval for data gathering was gained by components of the Ecosystems Services for Poverty Alleviation (ESPA) project, FICESSA's predecessor project, responsible for the data gathering. This project took place in the same community and the same information is gathered.

Though sensitive data such as salaries, food consumption patterns and living conditions is used, this data was not gathered by this component of the projects, and when used, only consolidated values are used. Personal identity of individuals was removed from the data prior to use. Therefore, there will not be an ethical implication for this specific project as all the data will be received from this personnel. The only reason why fieldwork might be required is to ensure that the data has been correctly interpreted and to ensure the system is understood correctly.

1.7 Research scope

The scope for this project consists graphically of the North-Eastern part of Swaziland (Tshaneni area as explained in **1.1** shown in Figure 1-1) since this is the area where the KDDP project is running. SWADE in combination with KDDP has piloted an alternative model that combines aspects of large- as well as small-scale production. The format of this project is relatively unique as the land owners (smallholders) got together to form commercial sugarcane enterprises by pooling their pieces of land together. All the smallholders who contributed land are then shareholders of the bigger enterprise. Local households who had land next to or close to the river had the option to get involved by donating their land and receiving shares of the company in turn. The farms are then managed through the use of a professional management structure. The structure of the management consists of directors, which may or may not be shareholders of the company. The directors are paid a salary and not dividends like the shareholders (Belmont Forum and FACCE-JPI, 2013) & (Terry & Ogg, 2016) & (Simelane, 2016) & (SWADE, 2012).

The only industrial crop that will be looked at during this project is sugarcane. The model that will be build will mainly include data collected from the specific area in Swaziland indicated by section **1.1** and will therefore mainly be applicable to the same area. The models constructed however, include general data that is applicable to a wider audience as well. The scope therefore consists of building a simulation model from data gathered from the specific area in order to answer the question at hand which is what the impact of industrial crops is on food security for Swaziland, Tshaneni.

1.8 Conclusion

This chapter gives an introduction for the research study as well as discuss the problem at hand. An overview of the area at which the study is based is also provided. The research objectives are stated and lastly the scope for the project is given.

The FICESSA project can have a big impact on the area and people where it is based. It could lead to new policies being implemented ensuring a food secure future for Swaziland. This emphasise that the model should be constructed as close to reality as possible in order for it to have the maximum possible effect. In order to build a model as good as needed, a lot of time should be spend to fully understand how systems thinking can be applied to model the specific case.

The next chapter aims to provide a thorough survey of literature in order to have the needed knowledge to build a model to solve the research problem.

Chapter 2 : Literature survey

2.1 Introduction

One of the factors causing a doubt in terms of the food security of Africa is that of expanding industrial crop production within the continent. There are many countries that struggle with this battle of food security, but one within the sub-Saharan context is Swaziland. Swaziland also has large industrial crop expansions and the influence of them on food security are not yet fully understood. It is believed that building a computer based simulation model will assist in understanding this system and related issues.

In order to overcome this issue, the facts regarding it have to be fully understood. This is only done through thorough literature reviewing and converting all of it to this specific topic and location. Therefore, the objective of this section is to do an extensive literature review on the topic at hand by breaking it down into five parts.

First, the definition of food security will be given and then how to measure it and why this is needed. Sequentially background will be given on Swaziland and its farming practices. The following section describes industrial crops and also its role in the Swaziland context. Next, different modelling techniques are analysed and reviewed in order to find the most appropriate one to model the problem at hand with. The last section of the literature review then describes the methods used to undertake the modelling.

2.2 Food security

According to FAO (Food and Agricultural Organization of the United Nations), (2006) there are four pillars on which food security can be based. These four are explained below.

Food availability

The availability of sufficient quantities of food of appropriate quality supplied through domestic production or imports, this includes food aid (FAO , 2006).

Food access

Individuals have access to adequate resources (entitlements) for acquiring appropriate food(s) for a nutritious diet. Entitlements are defined as the set of all commodity bundles over which a person can establish command given the legal, political, economic and social arrangements of the community in which they live (including traditional rights such as access to common resources) (FAO , 2006).

Utilisation

Utilisation of food through clean water, adequate diet, health care and sanitation to reach a state where all physiological needs are met and a state of nutritional well-being. This highlights the importance of non-food inputs within food security (FAO , 2006).

Stability

Stability is an important pillar of food security and for a population, household or individual to be food secure they must have access to adequate food at all times. The risk of not having food during certain cycles, (seasonal food insecurity) or of losing access to food as a consequence of sudden shocks (economic or climatic crisis) should be a minimum. This concept, therefore, refers to both the availability and access pillars (FAO , 2006).

2.2.1 Measuring food security

Food security in its full range cannot be captured by a single indicator, but rather through a variety of specific conditions, experiences, and behaviours that serve as indicators of the degrees of severity. Information like this can be gathered through different methods, but household surveys are in most cases the preferred medium and will usually be done in person through teams that physically go from household to household. These surveys include questions about the following conditions, events, behaviours, and subjective reactions (Bickel, 2000):

- Anxiety about having insufficient food or money to buy food to meet the basic needs of the household.
- Experiencing running out of food or having insufficient funds to buy food.
- Adjustments from normal food use.
- Perception about food eaten in regards to quality or quantity.
- Reduced food intake by adults or children within the household or frequency of feeling the sensation of hunger.

When referring back to the four pillars of food security mentioned above, there are multiple indicators that are applicable to each of these pillars. These indicators illustrate food security in a more quantifiable manner. The indicators, including the tools needed to gather information like this, are now explained as per pillar in Table 2-1 below (Lele, et al., 2016).

Table 2-1: Food security indicators as per the four pillars Adapted from (Lele, et al., 2016)

Parameter	Indicator	Tool	Scale
Availability	1: Stability of food price and supply	Crop production survey (area and yield by crop type),	Household and community levels
	2: Household food production		
	3: Food crop diversity		
Access	1: Sufficiency of household food consumption (Food Access)	Household consumption survey	Household and community levels
	1a: Percentage household expenditure on food		
	1b: Number of meals taken in a day		
	2: Household dietary diversity (Food Access)		
Utilisation	1: Degree of access to utilities and services (e.g. water, energy, health and sanitation)	Water, health and sanitation survey on access to services, including female education and infrastructure as well as access to energy	Household and community levels
Stability	Same as for Availability	Market monitoring – trade patterns and infrastructure, price and supply of key commodities	Community and key informant levels

2.2.2 Why measure food security

One hundred and eighty-six countries signed the Declaration of Rome at the 1996 International Food Summit, pledging that they will reduce the prevalence of hunger by at least half, each within its own jurisdiction by a target date early 21st century (FAO, 1996). Therefore, every country is concerned with their food security situation and continuously measure the level it's at. Food security is also an essential, universal dimension of household and individual well-being and the lack thereof leads to other related unwanted issues like health and developmental issues. Monitoring food security helps to understand the shortages in certain areas or for certain subgroups and to identify regions with severe conditions. This information helps public officials, policymakers, service providers and the public at large to assess the changing needs for assistance and the effectiveness of existing programs (Webb, et al., 2006).

It is important to notice that traditional income and poverty measures (GDP) do not provide information about food security (Webb, et al., 2006). Even though there is a relationship amongst these measures it cannot simply be said that if someone is poor they are food insecure (FAO, 2014). In the U.S. some case studies have shown that even though a household has a low-income, they can still be food secure. In contrast it also showed that a small percentage of non-poor households appeared insecure. It is not yet clear why this is the case, but it is influenced by many other circumstances which are in many cases difficult to pin down (Rose, 1999). Therefore, an independent measuring system is needed to measure food security.

2.3 Swaziland

Swaziland is one of Africa's smallest countries and is completely landlocked by South Africa and Mozambique. Most of the people (about 1.3 million) living in Swaziland live in rural areas (75% of the population), but since the country is so small, people are never too far away from urban areas. The country's economic stagnation in the last few years led to high poverty and unemployment rates. About 45% of Swaziland's population is considered poor as they live from less than US$1 per day (Tevera, et al., 2012).

With this poverty comes a variety of other problems as well, of which the largest is the high percentage of HIV positive people in Swaziland. Of the population of Swaziland, about 26% are HIV positive, this is amongst the highest in the world. This has lots of negative impacts on the country and also puts more pressure on the government to ensure health, as well as food security systems, are in place (Tevera, et al., 2012).

According to Tevera, et al. (2012) the country of Swaziland as a whole is extremely food insecure and has also since the 1990's shifted from being a food net exporter to being a net importer. An effect of this was that during the 2007 drought Swaziland received a lot of emergency food aid from international donors (FAO, 2007). Therefore, it shows that it is clearly not sustainable to rely on other countries to feed your people. In order to solve this problem, plans for self-production (in terms of food) will have to be made (Tevera, et al., 2012).

At the moment Swaziland farmers are only utilising 60% of the total arable land (1750 square kilometres) that is available, therefore the utilisation of all the available arable land might be one approach to increase food production. Alternatively, the yields that farmers currently get with their crops are extremely low and can definitely be raised through better management practices including the use of fertiliser (FAO, 2013) & (Zhukovskii, 2014). Currently, 97% of the arable land used, are used to plant either maize or sugar which therefore shows that industrial crops play a big part in Swaziland's agriculture.

Figure 2-1 below shows a comparison between the world and Swaziland's average maize yield per hectare over the past 55 years. It is clear that the agriculture sector of Swaziland is unable to obtain the same maize yields as that of the rest of the world. The significantly lower maize yields is one of the causes of food insecurity, since maize is a staple in Swaziland. The graph indicates an average maize yield of 1370 kg/ha for Swaziland in 2013 while it shows a 5465kg/ha maize yield average for the rest of the world.

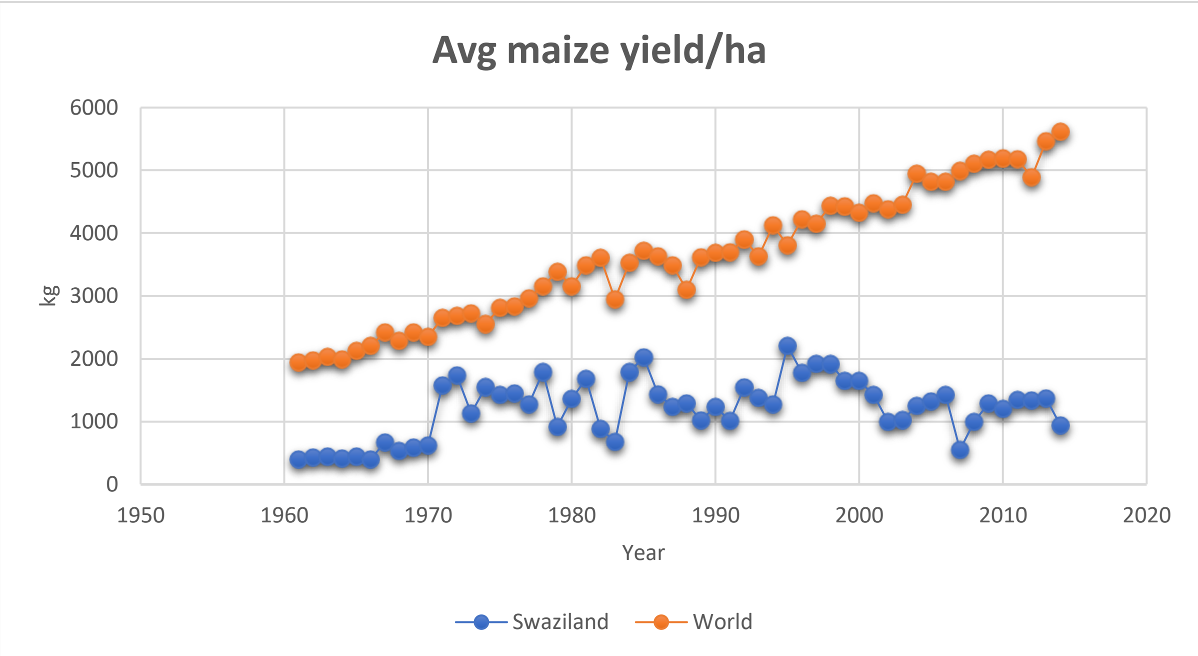

Figure 2-1: Average maize yield comparison between Swaziland and the World (FAO, 2017)

While Figure 2-1 points out that Swaziland is performing substantially below the world average when it comes to maize yield, Figure 2-2 shows the opposite for sugarcane yields. Swaziland performs better than the rest of the world when comparing the sugarcane yields of the past 55 years. In 2013 the average sugarcane yield for Swaziland was 96,667 tons/ha while the rest of the world were only able to achieve 70,711 tons/ha.

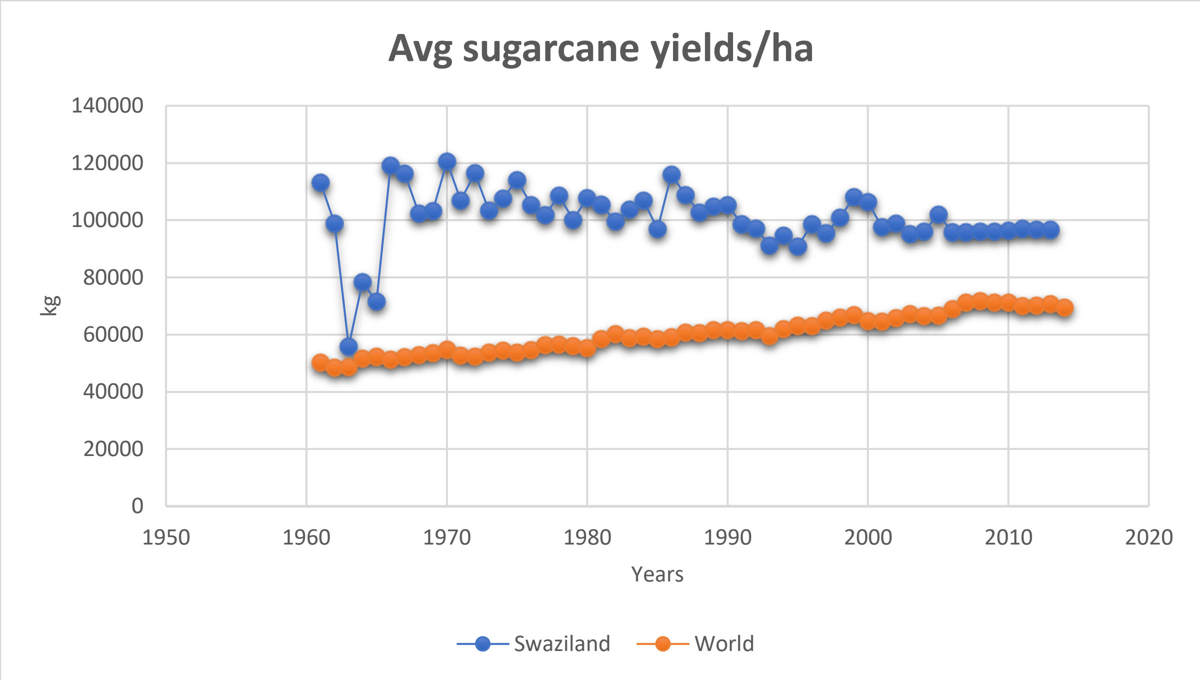

Figure 2-2: Average sugarcane yield comparison between Swaziland and the World (FAO, 2017)

2.3.1 Tribal land practices in Swaziland

Swaziland is one of the few countries left in the world that is ruled by a monarch which therefore cause ruling structures to be different from the rest of the world in terms of the country and their agricultural setup. In Swaziland, land tenure forms part of one of two groups, either Swazi National Lands (SNL) or Title Deed Land (TDL). These two groups account for 54 and 46 percent of the land area respectively. Tenure over SNL is not defined by legislation; the land is controlled and held in a trust by the king of Swaziland and allocated by tribal chiefs according to traditional arrangements. According to IFAD, UN-Habitat & GLTN (2012), the TDL and SNL are structurally divided as TDL consist mainly of large-scale farming practices whereas 61% of SNL farm holdings are less than one hectare in size and therefore can be categorised as small scale. (Some of the SNL holdings do go up to 5 hectares (Simelane, 2016).) As Swaziland's population increases it puts a lot of pressure on the available land for cropping and grazing, forcing households to use increasingly fragile lands to produce crops (IFAD, UN-Habitat & GLTN, 2012).

People who do want land in a specific area (where SNL is applicable), need to apply for a piece of land at the local chief who has the authority to approve or deny the application. When approved the applicant has to pay (not necessarily money) the chief in order to gain rights to the piece of land. Thereafter the applicant can farm on the piece of land as he/she wishes (Simelane, 2016). Pieces of land like these may or may not be close to the applicant's homestead.

The vast majority (over 70%) of Swaziland's people depend on subsistence farming for their livelihoods, which was greatly handicapped by recent droughts as well as a struggling economy (FAO , 2017). The standard farming practices for a subsistence farmer in Swaziland will consist of a piece of land where mostly maize, but also vegetables are grown. There are very few subsistence farmers who do irrigate, mainly because of the lack of funds for such investments (Simelane, 2016). According to Zhukovskii (2014), only 0,29% of the arable land in Swaziland is under irrigation. The farmer in most cases have livestock as well that grazes on tribal land that is not arable land. On this land, everybody in the community's livestock grazes (Simelane, 2016).

2.3.2 The Komati Downstream Development Project (KDDP)

The KDDP project has got a few major objectives which include reducing poverty through increasing household income and enhancing food security for the 20 000 to 25 000 beneficiaries (SWADE, 2012) & (Abou-Sabaa, et al., 2002). To provide irrigation to farms using water from the Maguga Dam and to facilitate the provision of credit financing to enable the farmer companies (explained below) to diversify and expand their business. Lastly to improve access to social infrastructures for the rural communities (SWADE, 2017).

The project has major targets that they would like to reach. These targets are listed below (SWADE, 2017).

- 6000ha of irrigated land
- 4500ha of sugarcane
- 1500ha of other crops
- 27 tunnels
- A pack house
- Nurseries
- Livestock projects

In order for the project to reach these objectives and targets a specific area where expansion like this was possible had to be identified and this area is the Tshaneni district as shown and explained in section **1.1**. This area was selected because of a number of reasons (beneficial for IC expansion) namely (Abou-Sabaa, et al., 2002):

Location

The 25 000ha area is situated on both sides of the *Komati River* from near Madlangempisi in the south-west to the border with South Africa near Mananga in the north-east. The area is shown in Figure 2-3 below.

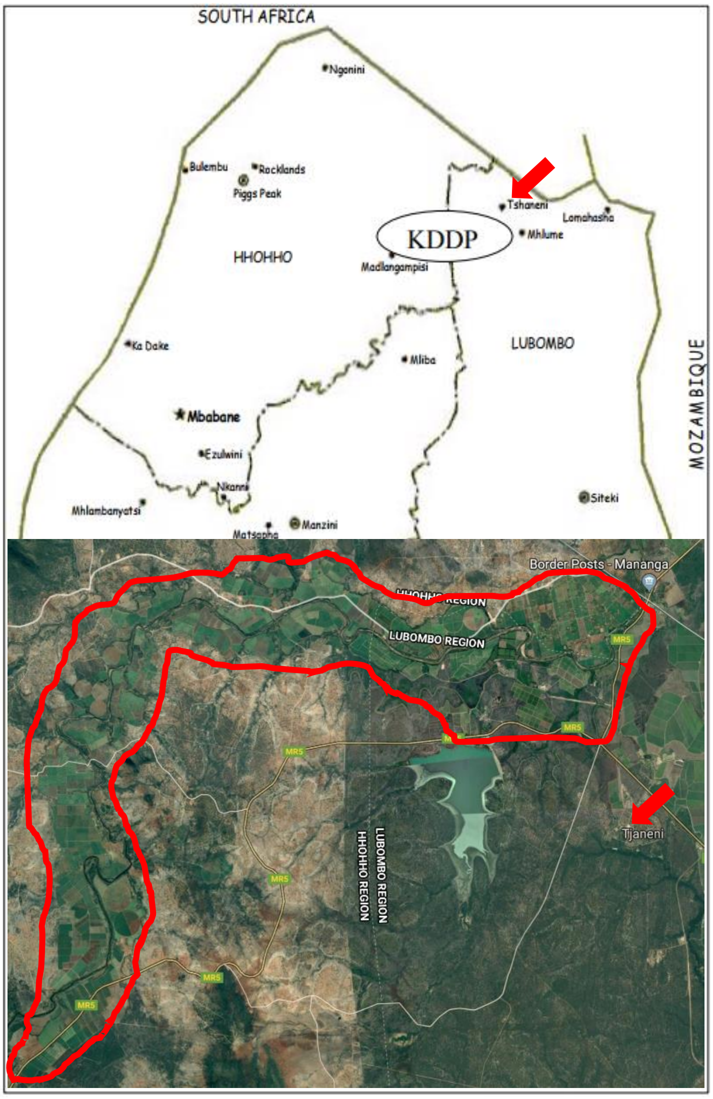

Figure 2-3: Map of Swaziland indicating the location of the KDDP project (Abou-Sabaa, et al., 2002) ; (Google maps)

Climate

The area is sub-tropical and semi-arid with a mean rainfall ranging from 550mm to 725mm with large inter-seasonal variations. Irrigation of 500mm to 1200mm will, therefore, be necessary (for sugarcane), depending on the seasonal rain. The area is elevated between 250m and 400m above sea level and summer maximum temperatures are around 35 degrees Celsius and winter minimums are 10 degrees Celsius, with no frost.

Vegetation

The vegetation of the area falls within the savanna biome which is among the largest in Southern Africa. In total eight variations of this biome is found within the project area, but the vegetation consists mainly of a mixture of tree and bushveld species. Forests and woodlands are also found in the area, as well as **some** dryland farming on isolated plots.

Topography and soils

The area consists of hills, foot slopes and plains ranging in altitude from 250m to 400m. The soils in the area are granite-derived and vary from shallow sandy loams to deep sandy soils with rocky outcrops. The soils of higher quality are perfect for sugarcane, while the soils of lower quality are still sufficient to grow food crops.

Demographic aspects and project beneficiaries

The project will positively affect 20 000 people of which 10 000 will be influenced directly through taking part in the project. The remainder will benefit from the generated economic activities. Since this area is a poverty-stricken area, mainly consisting of subsistence farmers, this will be welcomed.

The area elaborated on above was selected for the project and thereafter the required 6000ha had to be made available and this was done with the help of SWADE (Abou-Sabaa, et al., 2002). SWADE was established to plan and implement the *Komati Project* as well as the *Lower Usuthu Project*, and any other large water project that the Government may assign (SWADE, 2012). It originally was known as Swaziland Komati Project Enterprise (SKPE) (Abou-Sabaa, et al., 2002).

SWADE assisted the farmers through comprehensive training to form Farmers Associations (FAs) to establish and operate irrigation farms as profitable businesses in the area (Abou-Sabaa, et al., 2002). The farmers in the area gave their land (anything between 0,5 and 5 hectares) back to the SNL trust in order to form these FAs. Every farmer who had land in the specific area where an FA farm now exists became an equal shareholder (no matter what size farm they contributed) in that FA. The farmers also got the option to move to an alternative homestead which was provided or to stay where they were and receive a 30m by 30m (0,09 ha) block around their house to plant vegetables. It is important to note that if the farmers were to stay at their original homestead, then they received potable water as well as other incentives at their house, therefore this was a very popular option amongst the farmers. Even though it is not allowed, they do use this water to irrigate their crops (Simelane, 2016).

In total 27 FAs formed and rights for the land was acquired from the local Chiefs to establish their farming operations. The FAs take the financial risks and are also the holders of the water rights. (Funding mainly consist of loans from the African Development Bank (Abou-Sabaa, et al., 2002)) The farmers who are shareholders are not obliged to work for the FA, but rather the FA is run like a company with a board of directors (which may or may not be shareholders) (Simelane, 2016). A farmer had to contribute two hectares or more to satisfy the minimum requirements. The size of cultivated land of every FA varies between 200ha and 600ha, depending on the number of farmers in the association and the size of land the farmers could contribute (Abou-Sabaa, et al., 2002).

Figure 2-4 indicates different layouts of IC plantations (termed biofuel plantations in the figure) determined by the size of the IC plantation and the population density. The KDDP plantations are large scale plantations with no outgrowers as discussed in the previous paragraph. The population density in the Tshaneni area is considered medium, therefore the correct layout for these plantations will be type **e** from Figure 2-4. For the KDDP however some homesteads are situated within the IC plantations as explained.

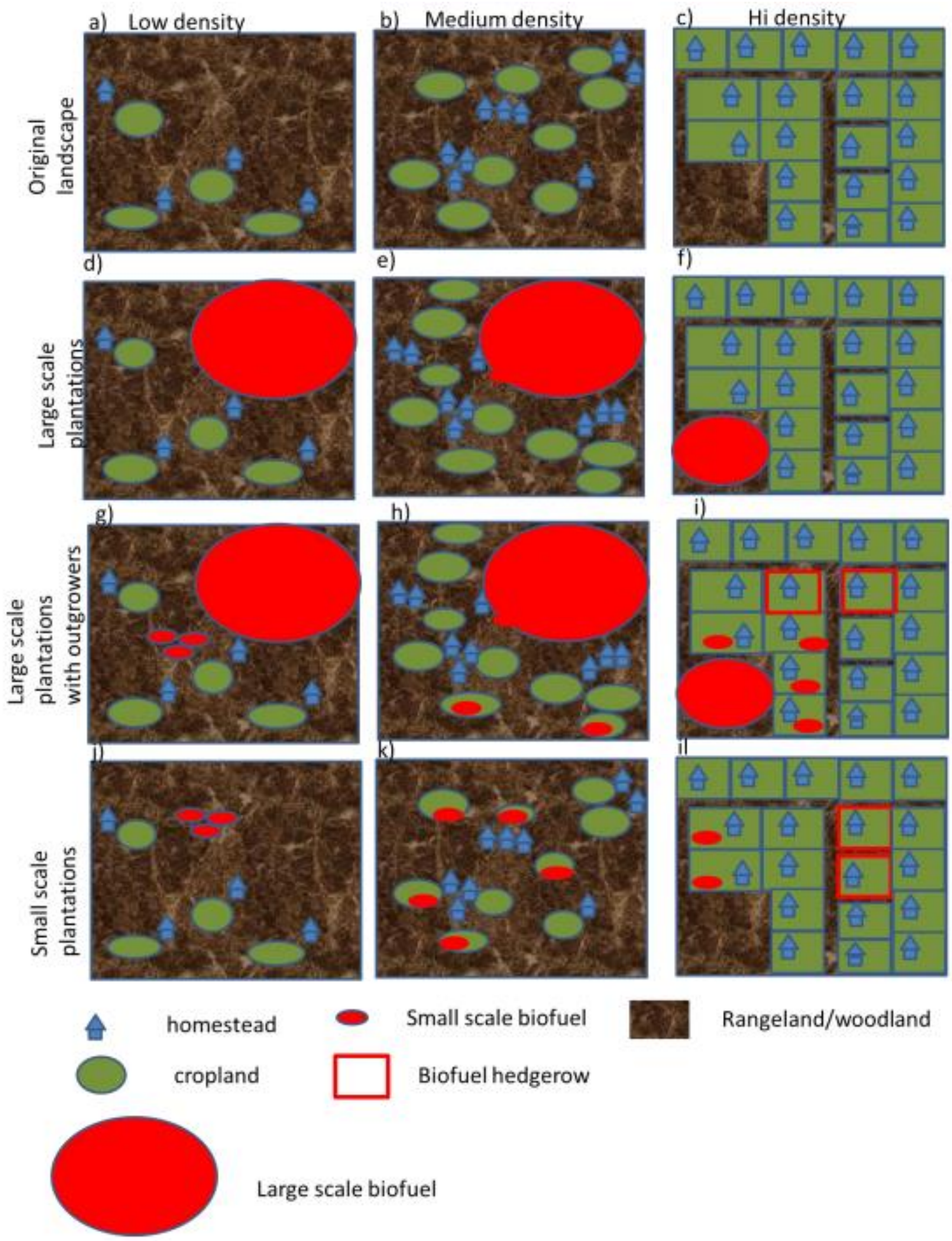

Figure 2-4: Plantation layouts determined by population density (Von Maltitz, 2017)

2.4 Industrial Crops (ICs)

The term "industrial crop" refers to an agricultural crop that is being planted for industrial use, rather than being nutritious food for human consumption. Industrial crops are therefore non-food crops that are used as fibre, rubber, chemicals, biofuels or any other industrial application (United States Department of Agriculture, National Agricultural Library, 2014). In many cases, the term "cash crop" is also used, because these crops are planted to generate monetary value. Industrial crops are planted as a commodity and/or as the raw material for industrial use (GRACE Communications Foundation, 2016). However, for this study it is believed that the type of processing that takes place after a crop is harvested can also class it as an industrial crop. Therefore, sugar cane is considered as an industrial crop for this study as it can be used as fibre, biofuel or energy. Tomatoes used in processing or maize used to produce biofuel are then also seen as ICs.

Most ICs need very fertile land and lots of water to grow, which in many cases were previously used for the cultivation of food crops. Some of the hallmarks of industrial crops include (GRACE Communications Foundation, 2016):

Mono-cropping

This refers to the practice of only growing one type of agricultural crop in a large area of land, year after year. This approach is used to take advantage of economies of scale since pesticides and fertilisers can be applied with large agricultural equipment which minimises human labour and harvesting across a large piece of land also saves on transport. However, mono-cropping is not only positive, as it puts a lot of strain on the environment and can also impose human health risks. The practice of mono-cropping became prevalent in industrial countries in the 1940s and 1950s, as farming became more commodity-based and less subsistence-based and as smaller family farms were consolidated into larger, industrial operations (GRACE Communications Foundation, 2016).

Intensive application of commercial fertilisers

Commercial fertilisers are products developed to add nutrients to the ground that the plants need in order to have larger yields. Most common fertilisers consist of a mixture of nitrogen, phosphor and potassium as these nutrients each focuses on a different part or time of a plants growth. When mono-cropping is practised and there is thus a lack of crop rotation, (which help to put back certain nutrients in the ground) fertilisers are more often needed for soil augmentation. Commercial fertilisers do improve plant yield, but also have certain impacts on the environment that lessen the usefulness of their application (GRACE Communications Foundation, 2016).

Heavy use of pesticides

Pesticide products destroy various agricultural pests like weeds, bacteria, fungi, and insects. The main driver for the heavy use of pesticides is mono-cropping and that the farmer wants to keep it that way, as all sorts of other crops, weeds or pests will only lessen the yield. There are however a few negative aspects of using pesticides heavily. This include the loss of biodiversity and elimination of key (positive) species, like bees that helps with pollination. In addition there is a health risk related to pesticides both for workers and consumers. It can also lead to water pollution and soil contamination. Pests resistance can develop which will cause stronger pesticides to be used or for it to be used more often (GRACE Communications Foundation, 2016).

Genetic engineering

Genetic engineering (GE) is the process of developing new species through introducing specific traits (genes) to animals or plants. This can be created synthetically or from existing organisms. GE crops have taken over as the USDA (United States Department of Agriculture) reports that as of 2011, 88% of corn, 94% of soybeans and 90% of cotton grown in the US is genetically modified. Most of the genes or traits introduced through GE are to protect or better them against mono-cropping problems, such as vulnerability to weeds and insects and also to achieve better yields. GE crops can negatively affect non-targeted beneficial insects like butterflies and bees and can also cause gene contamination of non-GE crops. GE crops might also have human health implications (many of which are yet to be understood). Currently, no laws exist that explicitly require products containing GE ingredients to be labelled as such, although products certified as organic may not have traces of GE ingredients (GRACE Communications Foundation, 2016).

Intensive irrigation

This is a common practice for industrial crop production, but cannot be limited to industrial crop production only as it is in many cases also used in food crop production. In most cases of the world, water for agricultural irrigation is taken from groundwater that does not replenish itself. Irrigation in this manner can also lead to salinization (deposits of salt) in the soil, which will lead to lower yields over time. In some cases, it also leads to the soil being drained from all the valuable nutrients which then requires, even more, commercial fertilisers to be used (GRACE Communications Foundation, 2016).

It is however believed that ICs can bring lots of development to a community. Development in terms of infrastructure, education, social opportunities, higher household incomes and empowerment (Abou-Sabaa, et al., 2002).

2.5 Modelling – Understanding and analysing complex systems

Models that are based on non-linear interactions and relationships are difficult to solve analytically, therefore, Sonnessa (2004) suggests that mathematical computation, based on iterative algorithms, should rather be used to solve or model these problems. Simulation is identified as the most appropriate method to understand complex models like this. What simulation does is it integrates and cumulates the effect of the “simple” processes over time and in complex “spaces.” Simulation also allows for prediction or modelling of a system outside of the time or space domain from which the data consists (Wainwright & Mulligan, 2013). According to Balestrini-Robinson, et al. (2009) the four most commonly used modelling and simulation methods are network models, system dynamic modelling, discrete event simulation and agent-based models. These methods will now be discussed, described and critiqued where applicable. At the end of this chapter, the preferred method to solve this complex problem will be selected and further described.

2.5.1 Network models

Network models (NMs) use nodes to represent different system mechanisms that bind the physical and relational connections between the system's "actors" (Ouyang, 2014). According to Goldenberg, et al. (2010) NMs have multiple application possibilities which include, but are not limited to; statistical modelling; analysing computer, social or physical networks or even organic networks models that can either be static or dynamic. Where a static NM displays and explains a snapshot, of a specific time, of a set of links in a model. Dynamic NMs focus on all the mechanisms that govern the network and network changes over time (Goldenberg, et al., 2010). Most early NMs were static, but as the potential of NMs was realised over time, dynamic NMs became more popular, also as more data became available and as interest grew in the field (Goldenberg, et al., 2010).

Figure 2-5 shows an example where an NM is used to help understand autism, the causes thereof and the influences of the different genes on one another. This was developed by Dr

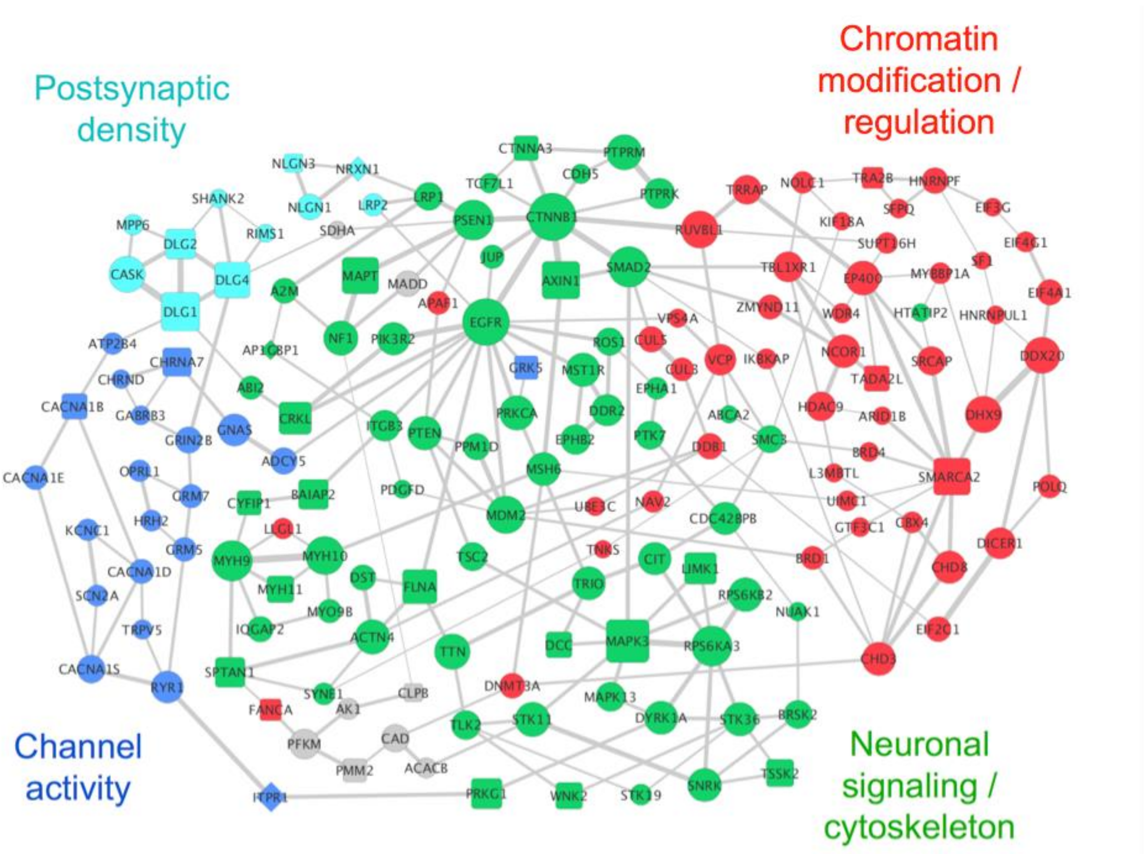

Figure 2-5: Network of autism-associated genes. (Credit: Dennis Vitkup) (Chang, et al., 2015)

Dennis Vitkup in order to link certain genes with certain symptoms, as every single patient's symptoms differ. The goal is to be able to make these linkages and then develop patient specific treatment to be as effective as possible (Chang, et al., 2015). This example does not reflect a "hard" optimisation problem but indicates the wide variety of applications for NMs. Bertsekas (1998) complements that by stating that NMs are ideal for both discrete and continuous optimisations. Even more so Newman et al. (2002) highly recommend NMs for social network analysis. According to them, social studies are appropriate because the can be broken down into three characteristic features. These three features include; (1) entities interact with each other without being conscious of it; (2) entities form clusters of interactions between each other; (3) the distribution of interactions between entities are skewed (Newman, et al., 2002). The most common optimisation problems for NMs are ones that fall into these categories (Bertsekas, 1998):

- Resource assignment
- Shortest path
- Transhipment
- Traveling salesman
- Multi-commodity flow

An NM's *anatomy* should be understood, as the structure has an effect on the network's function (Strogatz, 2001). For instance, the structure of a social network will affect the spread of diseases and information, whereas the structure of a food production system affects its robustness and ability to provide. Therefore NMs are built as separate systems/networks according to coherence, which then describes the inter-connections by inter-links, which provides flow patterns and creates a system diagram.

A number of algorithms are used in NMs to compute *characteristics* of graphs that describe a system. These graphs are then used to imitate the characteristics of real networks (Balestrini-Robinson, et al., 2009). NMs are however critiqued by Balestrini-Robinson, et al. (2009). According to them, NMs are only suitable for capturing functional complexities in the network and not able to capture space and time-dependent effects.

2.5.2 System dynamics modelling

System dynamics modelling (SDM) was developed by Jay Forrester during the 1950's. The reason for the development of it was driven by his training as an engineer, his knowledge and experience of feedback control loops from the Second World War, his love for management problems and having access to one of the first campus computers at Massachusetts Institute of Technology (MIT). The development of system dynamics led to the first significant understanding of supply chains and to be able to fully model the bullwhip effect (Yearworth, 2014). According to Richardson (2016), SDM is a computer-aided approach to policy design and analysis and can be applied in a very wide scope of problems and complex systems. It can be used to model complex scenarios within a social, economic, managerial or ecological environment and uses the relationships between these very different fields to build a model (Richardson, 2016). “System dynamics deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour and designing robust information feedback structures and control policies through simulation and optimization (Coyle, 1996).”

De Wit & Crookes (2013) are of opinion that the application of SDM has recently changed from business management problems to social, environmental, technological and agricultural systems. According to them, SDM is used to better understand complex problems and systems (De Wit & Crookes, 2013). Tedeschi, et al. (2011) defines SDM as a modelling approach that *“applies systems thinking to develop models that are used to describe (and simulate) the interactions among variables, by clearly identifying the behaviour of the variable”*. According to Stave (2003), SDM is used to evaluate problems based on an understanding that the structure of a system generates its behaviour. His definition of the structure is the way in which the different components are connected (Stave, 2003).

There are numerous fields in which SDM can be used, but recently, socio-economic problems have been very common problems to be solved using SDM. Figure 2-6 shows an example of SDM where it is used to model the child adoption cycle. SDM can also be used as a conceptual tool to help understand the dynamics and structure of complex systems (Tedeschi, et al., 2011). Stave (2003) adds to this by suggesting that SDM

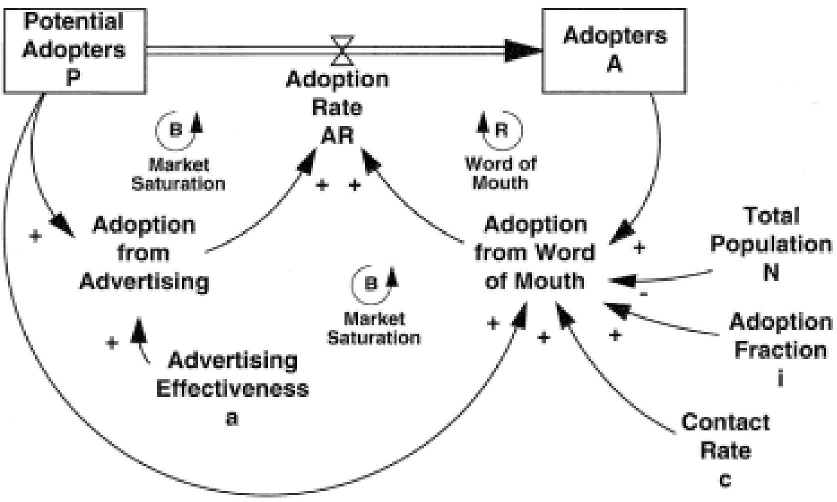

Figure 2-6: A system dynamics model of adoption (ETH Zurich, 2015)

should be used to assist managers to communicate with stakeholders. When using SDM in this way, managers can easily describe systems and their behaviours visually through the use of graphs and tables which undermines the need to explain all the technical details of the system to the stakeholders (Stave, 2003). The other fields in which SDM are applied to, include (Angerhofer & Angelides, 2000):

- work in corporate planning and policy design
- public management and policy
- economic behaviour
- biological and medical modelling
- dynamic decision-making theory development in the natural and social sciences
- energy and the environment
- complex non-linear dynamics software engineering
- supply chain management

Some of the critiques with regards to SDM include that it is difficult to determine the scope of the problem to be modelled. Also according to Balestrini-Robinson et al. (2009) in order to build a model, the modeller must understand the system and components from a multi-level perspective, which means that in most cases it will take longer to get to the place of building the model. Another difficulty when using SDM is to obtain accurate aggregated data (Balestrini-Robinson, et al., 2009). More critique for SDM comes from Pejic-Bach & Ceric (2007) who are of opinion that it is very difficult to understand the behaviour of the model if it is not developed incrementally and therefore suggests that a model should be developed *step-by-step*. This will combine the process of model building and evaluation, which allows for better understanding and gives more weight to the findings (Pejic-Bach & Ceric, 2007).

2.5.3 Discrete event simulation

Discrete event simulation (DES) is a computer-aided program that simulates a system by mimicking its behaviour. DES differs from other simulation types in the sense that it "*keeps track of the state of the system as time progresses*" according to Jacob (2013). This *state* can be described as the condition of the system at any given time of the simulation and any changes to this *state* occur at a time instant and are referred to as *events* (Jacob, 2013). Albrecht (2012) has a very similar definition of that of Jacob and state that it is a quantitative, mathematical simulation, based on time and event steps, which affects the state of the system. Brailsford & Hilton (2000) do agree with most of the statements above except that they see DES as a system consisting of a network of activities and queues. According to them the objects of the system are distinct entities, each with their own properties that control what happens to them over time (Brailsford & Hilton, 2000).

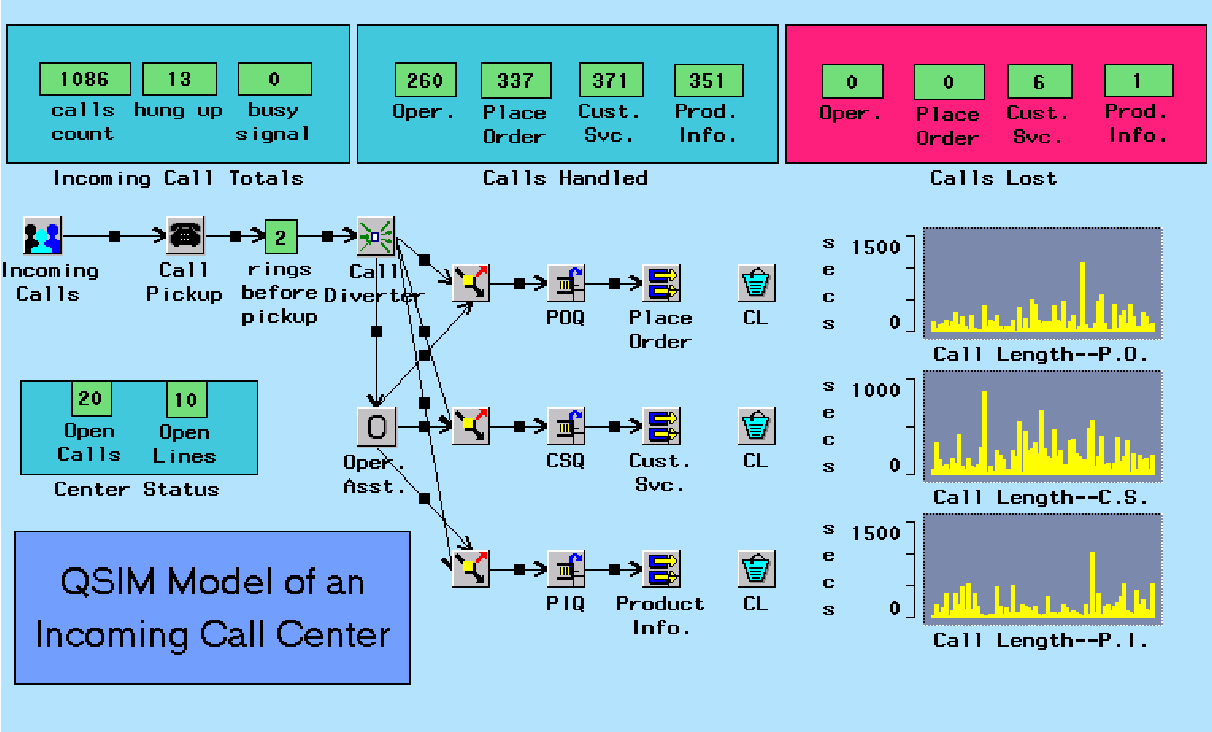

Figure 2-7: Discrete event simulation model through using QSIM for a call centre (SAS Institute, n.d.)

Figure 2-7 shows the system of an incoming call centre. Calls come in and are then directed to the different parts of the centre according to the client's needs. The structured shape is very systematic and clearly shows that the simulation happens sequentially. An *event* in this simulation refers to when a caller is diverted to a service point, while a change of *state* takes place when a customer has been served by a service point. The number of incoming calls, call lengths, open lines and call states are stored and visually represented through graphs and tables in the model (SAS Institute, n.d.).

Logistics companies prefer DES to model their supply chains, albeit not the only field it can be applied to, as it can be applied in almost anything in the manufacturing and service sector (Balestrini-Robinson, et al., 2009). Diaz & Behr (2010) is of opinion that DES performs at its best when answering efficiency-related questions. They highlight that DES is better suited to answer questions with regards to actions happening sequentially or entities flowing through queues and servers (Diaz & Behr, 2010).

Some of the critique with regards to DES includes that it is very difficult to simulate a model where entities require free movement or if a very detailed pattern should be followed (Balestrini-Robinson, et al., 2009). Another shortcoming of DES according to Maidstone (2012) is that it only focuses on the "small picture" or fine detail of the system. Since DES is stochastic it means that the model will give contrasting results on different runs, therefore it will have to be run multiple times to gain a full understanding of how the system works and what the real output will be (Maidstone, 2012).

2.5.4 Agent-based models

Agent-based modelling (ABM) is used when complex systems, consisting of interacting and autonomous *agents*, have to be modelled. These agents have specific behaviours that are governed by simple rules as well as interactions with other agents, which then again influences and determines their behaviours (Macal & North, 2010). Janssen (2005) agrees with Macal & North's view that states that ABM "*is the computational study of social agents as evolving systems of autonomous interacting agents".* Another definition of ABM that agrees with the above-mentioned definitions and state that it is a computerised simulation model of a number of decision-makers (agents) and institutions that interact through prescribed rules (Farmer & Foley, 2009).

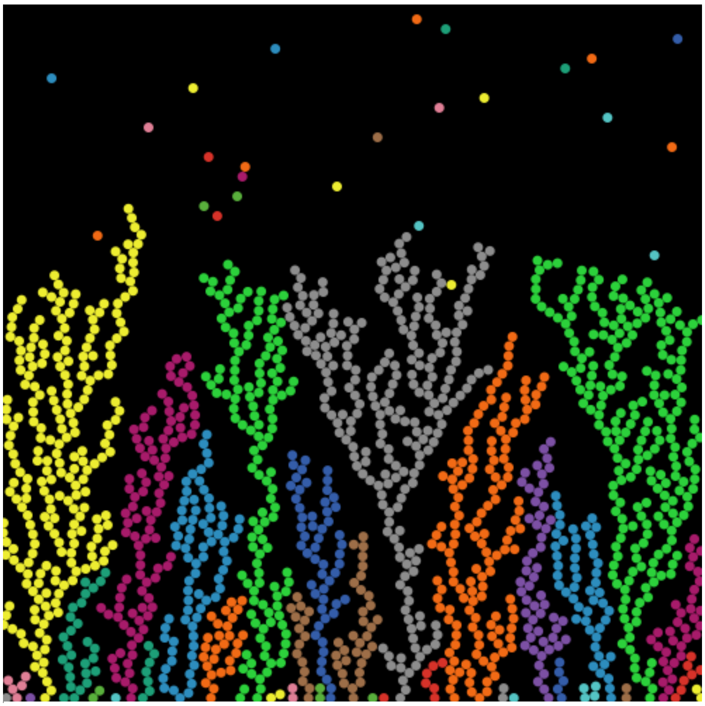

Figure 2-8: Agent-based model of diffusion-limited aggregation, done in NetLogo (Wilensky, 2005)

The example of an agent-based model seen in Figure 2-8 demonstrates diffusion-limited aggregation. It shows how particles (*agents*) that are moving (diffusing) in random trajectories stick together (aggregate) to form beautiful treelike branching fractural structures. This model replicates patterns that are found in natural structures like crystals, coral, fungi and lightning, just to mention a few (Wilensky, 2005).

According to Janssen (2005) and Macal & North (2010), ABM is a very good modelling technique to use when the modeller is concerned with the macro performance/outcome based on what happens at the micro level. They both agree that agents should be modelled individually, as they will have strategic interaction and coordination. Then the system's behaviour should be observed as patterns, structures and behaviours that are not explicitly programmed, but will emerge because of the interactions between the different agents (Macal & North, 2010) & (Janssen, 2005).

ABM consists of three main elements namely (Macal & North, 2010):

- *Agents* (including their attributes and behaviours)
- *Agent relationships* (including methods of how they interact with one another)
- *Agent environment* (including how agents interact with their environment)

Macal & North (2010) also state that agents have seven characteristics of their own, namely: Agents…

1. are *self-contained and uniquely identifiable*, which means that attributes can easily be identified as part of an agent or shared.
2. are *autonomous* and *self-directed*. This means that agents function independently in their environment.
3. have a *state*, that differs over time.
4. are *social* and influences other agents and their behaviours.
5. have the ability to *adapt* which therefore means that they can learn from previous experiences.
6. are goal-directed and have objectives to achieve.
7. can be heterogeneous and have various characteristics.

ABM can be applied in many different fields, from consumer purchasing behaviour to modelling agent behaviours in the stock market. From predicting the spread of a disease to modelling a person's immune system (Macal & North, 2010). Farmer & Foley (2009) is of opinion that ABM has the potential to model a complex financial economy.

Balestrini-Robinson et al. (2009) critique ABM as they say it is difficult to know what parts of reality should be modelled and that it is sometimes unclear which portions of the model can be characterised as independent events. Added to that, all interactions at the micro level are not always understood or explicitly modelled. Another problem Balestrini-Robinson et al. (2009) identifies is that models can easily become too complex to execute effectively. Lastly, they critique the fact that ABM models have to be run so many times in order for it to be accurate (Balestrini-Robinson, et al., 2009).

2.5.5 Modelling approach conclusion

For this research project, a single modelling approach has to be identified in order to achieve the project objectives. Through researching the different modelling approaches in chapter **2.5.1** to **2.5.4** and identifying their strengths and weaknesses, a decision can be made as to which approach to use. Table 2-2 shows each model's attributes as identified by Balestrini-

Robinson, et al. (2009). This summary assisted with the decision as to which modelling approach to use. For the type of research project that is being done, ease of creation and non-linearity are seen as the most important attributes, as there is a time limit to the study and because there are many non-linear interactions that have to be built into the model, as the research focusses on the agricultural field where people, the environment and economy are involved.

Table 2-2: Summary of modelling approaches' strengths and weaknesses, adapted from (Balestrini-Robinson, et al., 2009)

Attributes	Modelling Approaches			
	NM	SDM	DES	ABM
Ease of creation	Excellent	Good	Very poor	Very poor
Dynamic behaviour	Poor	Very good	Very good	Very good
Non-linearity	Very poor	Very good	Very good	Excellent
Interactions	Very good	Poor	Poor	Excellent
Ease of validation and verification	Very good	Good	Good	Very poor

One major setback of NM, in this case, is that it is not suitable for capturing space and time-dependent effects in a system. Another argument why NM is not suitable for this project is the fact that it is more suitable to understand inter-relational aspects between variables in a system and how the association between these variables work. Table 2-2 also points out that NMs are very poor at incorporating non-linearity relationships in a model.

SDM adheres to the most important attributes of this research project, namely that it should be easy to create and that it should be able to incorporate non-linear relationships. It is considered good and very good in these respective fields according to Table 2-2. Some shortcomings SDM have are that it is difficult to determine the scope of the model and also that the modeller needs to understand the whole system and all its components and their interactions, in order to build a sufficient model.

DES is rejected because it specialises in modelling supply chains and queues and also because it mainly focuses on the finer details, which sometimes means that the system is never evaluated or fully understood as a whole. This approach does require multiple simulation runs as it is stochastic, which is not ideal. Table 2-2 shows that DES is difficult to construct and build which unfortunately is a very important criterion in terms of this research project.

The last modelling approach namely ABM is also an appropriate modelling technique when considering for this project. It has the same shortcomings as SDM in the sense that it is difficult to determine the scope and that the whole system and all its components' interactions have to be fully understood in order to build the model. ABM, however, is less suited for this project than SDM owing to the fact that a model is constructed at an individual (micro) level. It is too difficult to identify the individual entities in the industrial crop sector of Swaziland and to identify their behaviour at micro and macro level. Table 2-2 indicates that ABM is very difficult to create and therefore is finally rejected, even though it is excellent at incorporating non-linearities.

SDM is therefore chosen as the preferred modelling approach to better understand the impact of industrial crops on food security in Swaziland. According to Table 2-2 SDM is the best overall performer as its biggest weakness is interactions between model entities and variables. The research problem at hand consists of multiple role players and entities and therefore falls directly into the scope of system dynamics modelling. The model will be built at a micro and macro level but will lean more towards the macro level as it can easily become too complex when only considering the micro-level perspective. SDM will provide a holistic solution as to what influence industrial crops have on food security in the country of Swaziland.

2.5.6 Modelling method review

System dynamics modelling (SDM) was identified in chapter **3** as the best method to model and investigate the impact of industrial crops on food security in Swaziland. The approach or methodology as to how this model will be built has to be defined. For this model to be as accurate as possible, the right construction method should be identified and followed. It is important to follow the correct way of building a model as it helps with confidence in the model and its results. This is very important, as the results of this model will be used to advise and communicate with stakeholders. According to Albin (1997) and Maani & Cavan (2012), there are two methods for building a functioning SD model. They are described and evaluated now after which the most applicable one is identified and used as a guideline to build the system dynamics model for this research project.

2.5.6.1 Method 1: Systems thinking and modelling process

This process consists of five different phases according to Maani & Cavan (2012). These five phases are described in Figure 2-9. Each phase consists of a few steps that explain in more detail what that step entails. The phases and their steps are explained now as described by Maani & Cavan (2012).

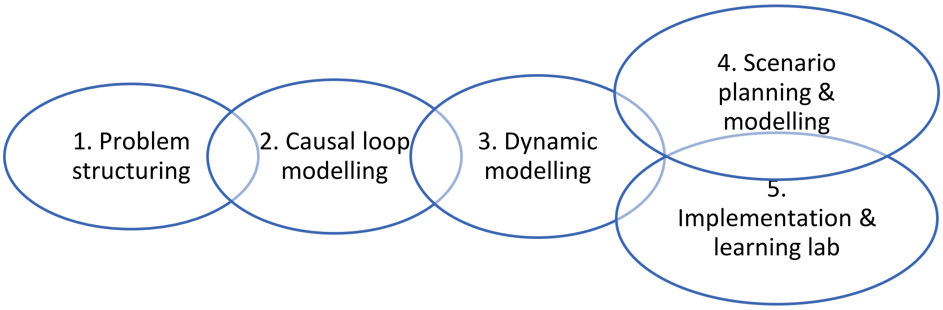

Figure 2-9: Five phases of the systems thinking and modelling process. Adapted from (Maani & Cavan, 2012)

1. Problem structuring:

During this phase, the problem and other background data are identified and gathered. The other background data include who the stakeholders are, policy issues, and data helping to clearly identify the objectives of the study. Other preliminary data should also be collected during this phase and the problem should be analysed through a holistic approach. Analysing the problem with the use of the doughnut principle is advised. This principle is defined as looking at the macro as well as the micro level of a problem and understanding both.

2. Causal loop modelling:

In order to develop a causal loop diagram (CLD), all the main variables have to be identified as well as the behaviours and relationships between them. CLDs are developed to illustrate the relationships between the different variables. It is a very effective way of explaining to stakeholders how the problem is currently understood and easy to see whether the model will address the identified issues or objectives identified in phase 1. This phase therefore helps improve the conceptualisation of the system and its behaviour.

3. Dynamic modelling:

In the dynamic modelling phase, the physical model is built. All relevant variables (including initial values) are defined (stocks, flows, etc.) and data concerning them, their behaviours and relationships are gathered. The model is then constructed from the CLDs (phase 2), which are used as a backbone to build stock and flow diagrams (SFDs). After construction of the model, validation takes place and then sensitivity analysis is done as to see which areas of the model are most sensitive to change.

4. Scenario planning & modelling:

During this phase, the modeller determines what scenarios will be tested. Scenarios are a combination of events or policies. It is important that scenarios include the key drivers that will test or display the needed variables in order to answer the questions with regards to policy and the objectives. They are done by only changing certain variables and then running the model. Usually, there will be a base scenario, where everything is set as to how the model was originally built. Other than that, it is the modeller's choice as to which scenarios will be run, but a common approach is to at least run an *optimistic* and a *pessimistic* scenario.

5. Implementation & learning lab:

The model that is built is now improved through the use of *microworlds*. *Microworlds* are tools that are used by stakeholders and managers to experiment with models themselves. This is a very effective way for all involved parties to learn about the model, its outputs and validity.

2.5.6.2 Method 2: Building a system dynamics model

The second method described consists of four phases, which each have a few steps under them (Albin, 1997). Figure 2-10 shows the four phases of building a system dynamics model. These four phases are explained below as described by Albin (1997).

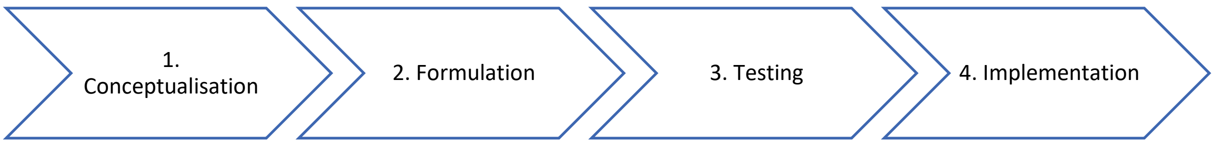

Figure 2-10: Phases for building a system dynamics model. Adapted from (Albin, 1997)

1. Conceptualisation:

This phase includes multiple actions, namely defining the purpose of the model, determining the boundaries of the model and defining all the key variables of the system. The intended use of the model, as well as the audience, are identified. Reference modes are drawn that describe the expected behaviour of the key variables. (It is used later on to determine the validity of the model at a very simple level.) In addition to all of this, the CLDs for the system is also constructed. The first phase of this method is very similar to the first two phases of the previous method described.

2. Formulation:

Converting the feedback loops from concept to mathematical equations is the first step of this phase. Next, all the system parameters are determined and then finally the system dynamics model is constructed. This phase again is very similar to phase 3 of the previously discussed method.

3. Testing:

During this phase, the model is tested through simulation. All assumptions are evaluated and the reference modes are used to validate the behaviour of the model. Sensitivity analysis is also done in this phase.

4. Implementation:

In the final phase of this method, different policies and scenarios are tested through the model. The results of the tests are used to recommend certain policy changes or advancements to the stakeholders. The results and recommendations can then be used as decision-making tools for stakeholders.

2.5.6.3 Modelling method conclusion

Even though the methods described in this section are very similar, they do have very different approaches considering stakeholder engagement and inputs. The first method includes stakeholders input in the first phase, which is an advantage if the stakeholders have identified the problem and approached the modeller to solve or model it. Critique on this is approach is that if it is unclear who the stakeholders are or if the problem is identified without stakeholder input, then it can be difficult to get the right stakeholders to give input and validate the model. Therefore almost making the model obsolete, as the aim of models like this is to give stakeholders insights into certain problems. The second method tries to rather identify an audience for which the model will be built. Then only in the final phases, stakeholders are consulted. Another difference between the two methods is that the second method’s phases’ descriptions are very vague compared to that of the first method from Maani & Cavan (2012).

Method 1 is the most appropriate approach for the purpose of this study, as the research problem has already been identified and is part of a bigger international project as mentioned in the previous chapters. Engagement with stakeholders is part of this project scope as well, which favours method 1 even more. Another advantage of method 1 for this project is that it has well-defined steps. Therefore method 1: *Systems thinking and modelling process* from Maani & Cavan (2012) is selected as the approach to build the system dynamics model for this project.

2.5.7 Similar problems solved with modelling

It is the first time that this strategy will be applied to a food security problem. Table 2-3 shows where system dynamics have been used to approach different food security problems. It however, seems to be the first to specifically focus on the impact of ICs on food security. It also will be the first for the Swaziland context.

Table 2-3: System Dynamics already done on food security (Giraldo, et al., 2008)

MODEL	EMPHASIS
(Bach & Saeed, 1992). *Food self-sufficiency in Vietnam: a search for a viable solution.*	Studies various possible solutions to self-sufficiency on food (supply) in Vietnam.
(Bala, 1999). *Computer Modelling of Energy, Food and Environment: The case of Bangladesh.*	An integrative Vision of energy, food and environment applied to Bangladesh.
(Gohara, 2001). *A System Dynamics Model for Estimation of Future World Food Production Capacity.*	Analysis of supply and demand of food worldwide.
(Meadows, 1976). *Food and Population: Policies for the United States.*	Analysis of supply and demand of food as well as demographic changes.
(Meadows, 1977) *The World Food Problem: Growth Models and Nongrowth Solution.*	Analysis of the global food problem as seen from both, growth models as well as nongrowth models approach.
(Quinn, 2002) *Nation State Food Security: A Simulation of Food Production, Population Consumption, and Sustainable Development.*	A model simulation that links food production, the requirements of the population consumption and sustainable development.
(Saeed, et al., 1983) *Rice Crop Production Policies and Food Supply in Bangladesh.*	Policy analysis applied to rice and food supply.
(Georgiadis, 2004) *A system dynamics modelling framework for the strategic supply chain management of food chains.*	Analysis on the management of food supply chain.

(Saeed, 2000) *Defining Developmental Problems for System Dynamics Modelling: An Experiential Learning Approach*	Application of a model to constructing a reference mode addressing the food security problem in Asia.

2.6 Conclusion: Literature survey

This chapter focussed on providing information from literature supporting the research as well as help to better understand the impact of ICs on food security for Swaziland, Tshaneni. First the term food security was discussed and defined and also how to measure it as well as why. Next Swaziland's farming practices and potential was discussed. Tribal land practices and information regarding the current IC project (KDDP) is given. Industrial crops are defined and explained as well.

Subsequently four different modelling methods are reviewed in depth and system dynamics modelling is chosen as the preferred method. This leads to a thorough method review section that compares two modelling approaches of which the first method is chosen. Lastly similar problems that have been solved using SDM are discussed.

The next chapter follows the steps of the modelling approach chosen to illustrate the modelling methodology as well as the construction of the model. The model is also validated in the chapter and different scenarios are defined.

Chapter 3 : Modelling methodology

The phases described in method 1 in section **2.5.6.1** are used as guidelines from now onwards. Even though as part of the bigger FICESSA project the *Implementing and learning lab* phase will be executed it is not part of the scope of this thesis and is therefore excluded from this chapter. Therefore, the rest of the chapter uses Figure 2-9's first four phases as a guideline and explain in detail what is done in every phase.

3.1 Problem structuring

The problem is properly defined and the scope and boundary are set in this section. Maani & Cavana (2012) defines this as the first step to solve any problem. They are of opinion that the importance of this step is underestimated by most managers and stakeholders.

3.1.1 Problem areas

In order to build a model, a few key concepts have to be fully understood. These include the gap, dilemma and problem statement. The gap is the difference between how things are and the ideal situation. Then the dilemma refers to the factors that oppose one another in solving the problem. The problem statement is the problem in a summarised sentence and combines the problem and the people involved. The gap, dilemma and problem statement, when referring to the Swaziland case, are explained below. The real-world examples are used to clearly indicate what each concept means.

Gap

Due to the widespread poverty and food insecurity in Swaziland, there is a need to improve family incomes (or GDP/capita) and improve food security. Increasing income per capita can reduce food insecurity by improving food access and stability.

Dilemma

However, the conversion of land from food crops to industrial crops, (like sugar cane) can reduce food availability and hence food security.

Problem Statement

The conversion of land from food crop to industrial crop production can increase food security by increasing incomes, but could also lead to poverty/hunger by reducing food availability.

3.1.2 Model boundaries and time frame

The model time horizon is set from the year of 2016 (t_0), as this is the first year from which the data (surveys) for this project is gathered, to 2035 (t_n). The year 2035 was chosen, since the model's aim is to help understand what impact IC expansion has on food security, for the people of Swaziland, but more specifically the people of the Tshaneni district, over the long term. The question is whether ICs will have a positive r negative influence on food security after 20 years. This timeframe was also chosen to keep it short enough to clearly see the sensitivity, but long enough to make it applicable to long-term goals. Something important to note is that the model is run in months, but the time horizon is set in years. The model is run in months because there are many different "cycles" in the model that all finish during different months of the year and therefore would not have been represented correctly if modelled in years.

As explained in sections **1.3.2** & **2.3.2** the physical boundaries of the model is that of the KDDP area on the northern border of the Hhohho and Lubombo provinces, close to Tshaneni.

The model is categorised into six sub-models that can be seen in Figure 3-1. All the input variables and outputs are categorised into these six sub-models. It is important to note that the six sub-models are not independent, but rather very inter-dependant. A summary of each component and their inter-dependency is given below.

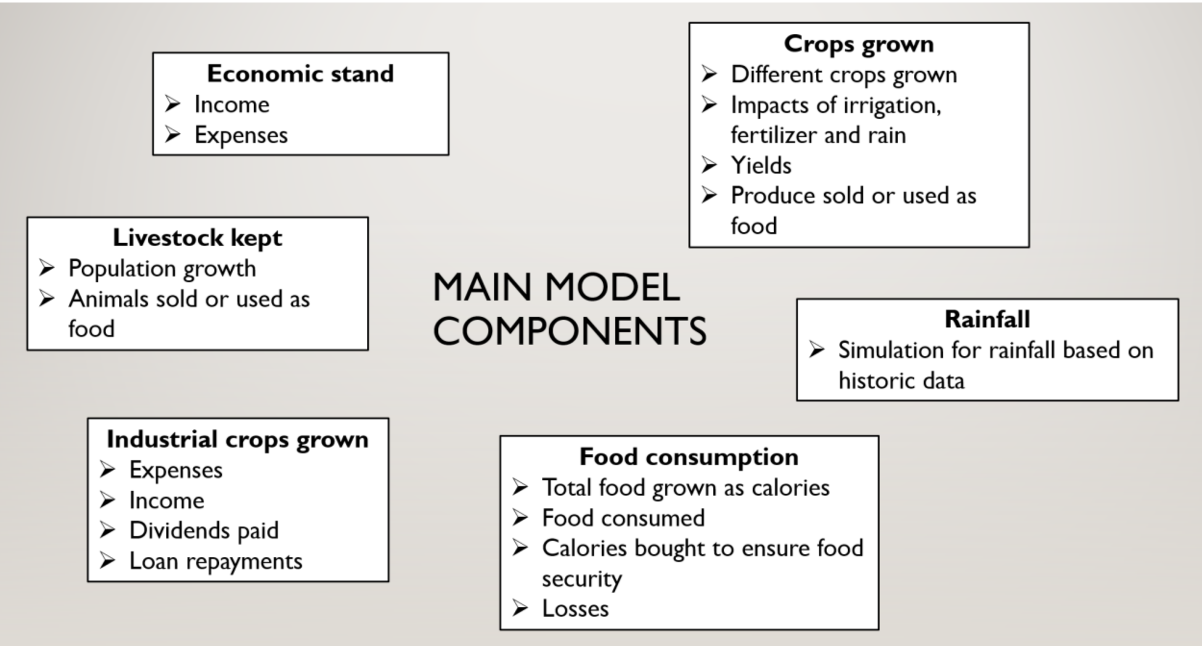

Figure 3-1: Main model components for this project

Economic stand

The economic sub-model interprets all income and expenses of a household. (Important to note that the model is based on the food security of a household) This sub-model is directly dependent on all the other models except for the *Rainfall* model on which it is indirectly dependent.

Livestock kept

The aim of this sub-model is to keep track of livestock populations kept by each household. It keeps track of their births and deaths, as well as the amount sold. It therefore directly influences the *Food consumption* and *Economic stand* models.

Industrial crops grown

The structure of how industrial crops are farmed in terms of the FAs are portrayed through this sub-model. It includes all the expenses as well as income. It also includes the repayment of the loan and the payments of dividends to the shareholders, which directly influences the *Economic stand* model.

Food consumption

All the available food (in terms of livestock, food crops grown and bought) is converted to calories in this sub-model and then consumption and losses are also taken into account. Other models that directly influence the *Food consumption* model are the *Livestock kept* and *Crops grown* models.

Rainfall

The rainfall sub-model simulates rainfall for the Tshaneni area based on historical rainfall data. It directly influences the *Crops grown* model, but are not dependent on any of the other sub-models.

Crops grown

The crops grown by a household is modelled here. The effect of fertilizer, rain and irrigation on crop yields are modelled in this sub-model as well. Therefore, this model is directly influenced by the *Rainfall* and the *Economic stand* sub-models. (*Economic stand* sub-model, because the amount of fertilizer bought is directly dependent on the amount of money available.)

Of the four food security pillars, three are modelled namely; food access, food stability and food availability. The main variables used to indicate the state of a household's food security are *Money available* and *Calories available*. *Money available* indicates food access as well as to food stability. *Calories available* on the other hand indicates food availability and food stability. (In reference to section **2.2**)

3.1.3 Data gathering

Multiple public and private organisations were consulted in order to obtain useful data to build, improve the accuracy and validate the model behaviour. One leg of the FICESSA project was data gathering through household surveys. In total 693 household surveys were conducted in the Tshaneni area. The 44-page survey is very thorough and include questions regarding (FICESSA, 2016)

- the respondent's profile
- the household demographic profile
- agroeconomic practices
- reliance on environmental resources
- food security
- income and livelihood sources
- sugarcane/cotton smallholders/outgrowers
- employees in industrial crop plantations
- effects of the name of IC industry
- Wellbeing
- general comments

All additional data used to construct the model was gathered by searching through literature using Google scholar. All the data found in literature as well as their sources can be found in **Appendix B**. A process called mediated modelling was used in order to ensure the models represent reality. Mediated modelling is an approach that brings together diverse interests to raise the shared level of understanding and foster a broad and deep understanding. It is based on a structured system dynamics process in which community members, government officials, industry representatives and other stakeholders work together to produce a coherent, simple, but elegant simulation model (Van den Belt, 2004).

Simplistic models were built with relationships between variables as understood and then people from these different fields were approached and asked whether they agreed with the logic, relationships and understanding. Whenever suggestions were made, changes were made until there was consensus between all the parties about the basics behind the model. For this reason, field work was done in Swaziland, as it is very important to fully understand the dynamics of the whole system. All data used to build the model can be found in **Appendix B**. The variables are classed into three tables depending on whether they are exogenous (Table A-0-1), endogenous (Table A-0-2) or excluded (Table A-0-3). (Interesting note from the data is that purchasing food is a lot more expensive than what the farmers receive for their produce, up to three and a half times more expensive. It causes interesting dynamics in the model. This can be seen in Table A-0-1.)

3.2 Causal loop modelling

In order to better understand the structure and behaviour of the impact of industrial crops on food security for Swaziland, CLDs are created. It helps to identify the key role-players in the system and how they interact and influence each other. A CLD provides the foundation for the stock and flow diagram in which role-players can be classified as a stock, flow, auxiliary or exogenous variable (Maani & Cavan, 2012). An example of a CLD that illustrate chicken population with regards to road crossings is shown in Figure 3-2 (Tom, 2010). The three variables are *Eggs*, *Chickens* and *Road Crossings* as it can be seen in Figure 3-2. If there are more *Eggs* that hatch, then the number of *Chickens* will increase, therefore the influence on *Chickens* is positive (+) since an increase in *Eggs* leads to an increase in the number of *Chickens*. The more *Chickens* there are, the more *Road Crossings* there will be, therefore the influence of the number of *Chickens* on *Road Crossings* is positive (+). As the *Road Crossings* (synonym to the chance of death in this case) increase, the number of *Chickens* will decrease, which implies a negative (-) influence. Lastly the more *Chickens* there are, the more *Eggs* will be laid and therefore the influence is positive (+).

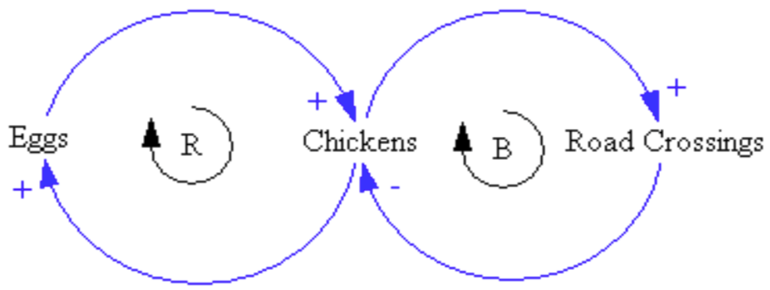

Figure 3-2: A causal loop diagram about chicken populations and road crossings (Tom, 2010)

Reinforcing loops (R) are positive feedback systems, which indicates that a certain feedback loop either represents a systematic increase or decrease. Reinforcing loops should be modelled very carefully, as it can spiral out of control very easily and cause uncertainty in a model (Maani & Cavan, 2012). A feedback loop is considered *Reinforcing* if it contains an even amount of negative (-) causal links (Kim, 1992).

Balancing loops (B) are the opposite of *Reinforcing loops* and are negative feedback systems which alter direction of movement/feedback (Maani & Cavan, 2012). This results in a loop that fluctuates and strives towards equilibrium (Haraldsson, 2000). The feedback is considered

Balancing if it contains an uneven amount negative (-) of causal links (Kim, 1992). (There are some exceptions to the rule.)

All the different CLDs constructed to build the model is described in the rest of this section.

3.2.1 Economic stand CLD

Figure 3-3 illustrates the *Economic stand CLD,* which can also be seen as the expanded CLD for the model as a household's *Money available* is directly influenced by all the other sub-

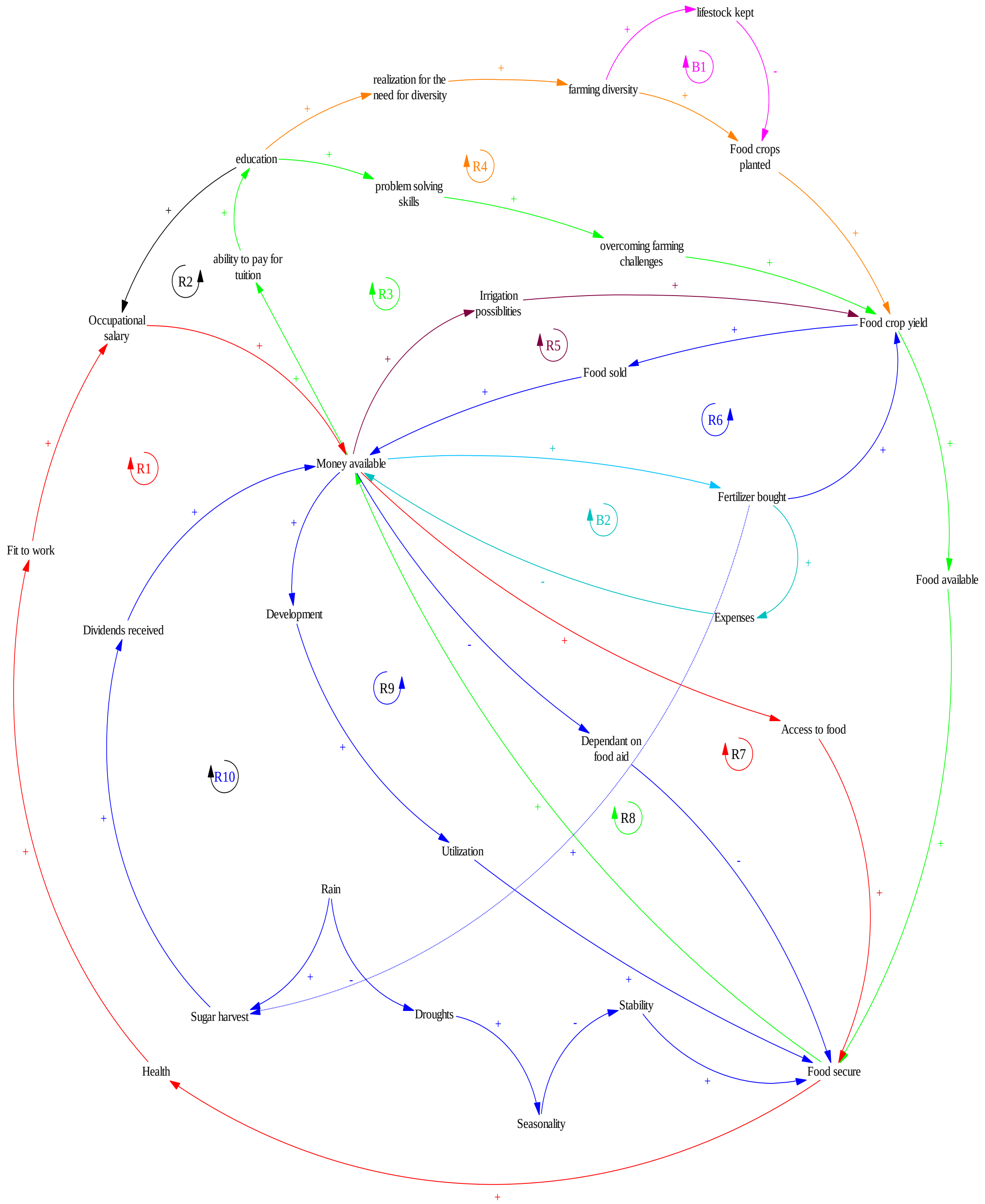

Figure 3-3: Economic stand CLD

models, except for the *Rainfall* model of which it is indirectly dependent. For this reason, all the other models' main variables are also included in this CLD.

Feedback loops R1, R3, R4, R5, R7, R8, R9 and B1 all have a direct impact on food security as shown in Figure 3-3. Feedback loop R1 depicts the effect that health and occupation have on food security and will be explained in more detail below. Another loop that will be explained in more detail is feedback loop R3 of Figure 3-3 which indicates the impact that education has on a household's food security.

The reinforcing feedback loop (R1) displayed in Figure 3-4 indicates the impact of *Health* and *Occupational salary* on *Food security*. As the *Occupational salary* increase, the amount of *Money available* also increases, which implies a positive relationship as indicated by the +

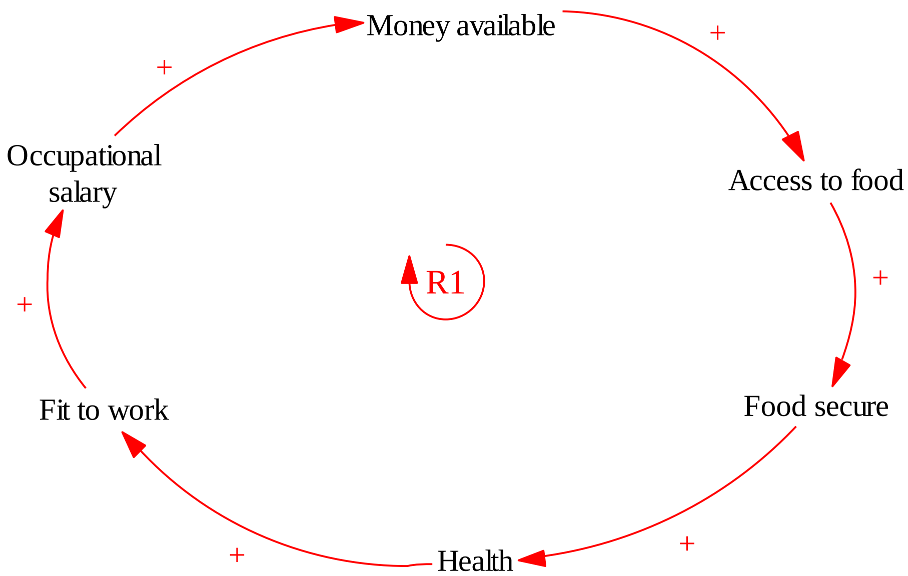

Figure 3-4: Reinforcing feedback loop indicating the influence of health and occupation on food security

sign in Figure 3-4. When there is more *Money available*, there will also be more *Access to food*, as food can be purchased. More *Access to food* leads to being more *Food secure* as explained in section **2.2** through the four pillars of food security. Being more *Food secure* also means more (better) *Health* and when someone has better *Health*, they will be more *Fit to work*, which in turn will mean more *Occupational salary* as less sick leave will be taken. As time goes by, the variables will have a reinforcing effect on one another which should cause a gradual increase in this case.

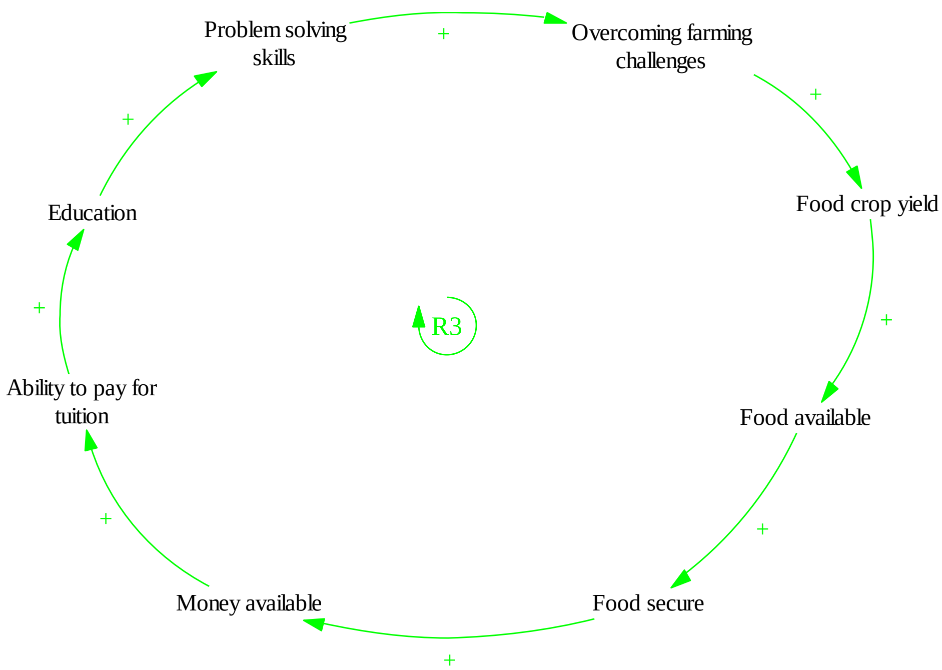

Figure 3-5: Reinforcing feedback loop of the impact of education on food security

Figure 3-4 illustrates a feedback loop that points out the impact of education on food security. The loop is a Reinforcing loop with the variables as shown. As a household has more *Money available*, their *Ability to pay for tuition* increases, therefore the relationship is positive (+), like for all the other relationships in the feedback loop represented in Figure 3-5. If the *Ability to pay for tuition* increase, then more people will go to school and receive *Education*. An increase in a person's *Education* will lead to an increase in their *Problem-solving skills.* More farming challenges will be overcome when a person has more *Problem-solving skills*. This, in turn, will result in better *Food crop yield*, which will mean that there is more *Food available.* When a household has more *Food available* they will be more *Food secure* as food availability is one of the four pillars of food security discussed in section **2.2**. Lastly, if a household is more *Food secure* then they will have more *Money available* to spend on other expenses, as they have enough food. There will thus be a reinforcing effect in this loop as time goes by.

3.2.2 Livestock kept CLD

The CLD indicated in Figure 3-6 shows the base from which the SFD for the Livestock kept sub-model was built. It is important to note that the CLD is generic for all the different types of livestock modelled which include cattle, goats, pigs and chickens, as these livestock are the most commonly kept animals by the people in the Tshaneni. (Indicated through the FICESSA survey data as explained in section **3.1.3**) Important to note as well is that *Money available* forms part of this CLD as it links this feedback loop back to the extended/Economic stand CLD.

There are two balancing loops (B1, B2) and one reinforcing loop (R1) in the Livestock kept CLD shown in Figure 3-6. R1 illustrates that more Livestock will lead to more *Births* and as more *Births* happen, there will be more *Livestock*. Therefore there is a positive (+) relationship in both directions. In B1 it can be seen that when the *Livestock* numbers increase, then the

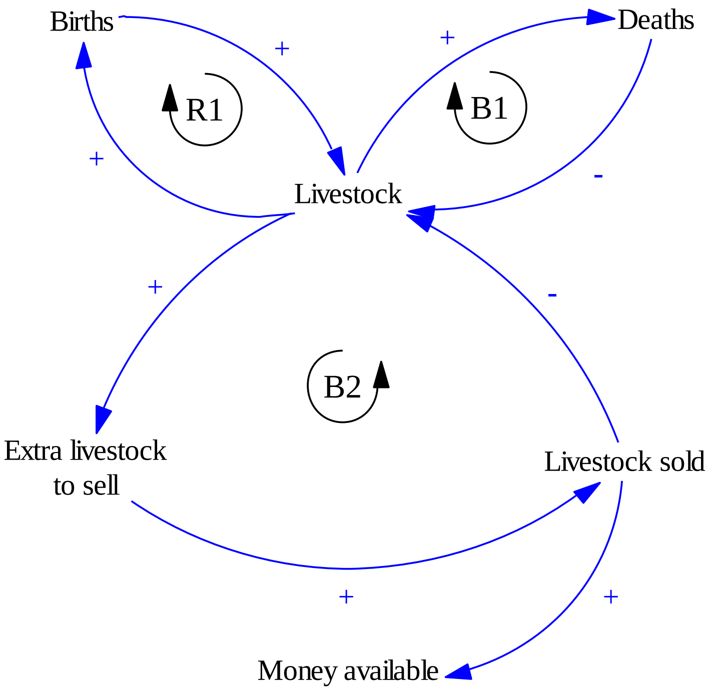

Figure 3-6: Livestock kept CLD

number of *Deaths* will also increase making it a positive (+) relationship. The opposite is true from *Deaths* to *Livestock* because, as the number of *Deaths* increase, the amount of *Livestock* decreases, therefore the relationship is negative (-).

The selling of livestock is portrayed by B2 in Figure 3-6 where it can be seen that whenever there is more *Livestock*, there will be *Extra livestock to sell*. When there is *Extra livestock to sell*, then more *Livestock* will be *sold* which will lead to a decrease in the number of *Livestock* and therefore causes this feedback loop to be balancing.

3.2.3 Industrial crops grown CLD

The CLD used to build the *Industrial crops grown* stock and flow diagram is illustrated in Figure 3-7. It shows all the relevant variables as well as which variables interact with which. It also shows the type of relationships between them. The variable *Dividends paid* is the direct link back to *Money available* as shown in Figure 3-7 which is how this sub-model directly influences the *Economic stand* model. The two variables *Rain* and *Sugar price* are external variables and therefore no other variable has an influence on them.

The diagram consists of five balancing loops and two reinforcing loops. They are all equally important, but only B1 and R2 will be explained in more detail now.

For B1, the more *Company money available*, the more *Fertilizer* will be *bought*, which will then increase the amount of *Fertilizer applied* that should increase the *Sugarcane yield*. Therefore all the links between these variables are positive (+). When the *Sugarcane yield* increases, then the amount of *Sugarcane harvested* will also increase and there will be more *Sugarcane sold*, which will, in turn, increase the *Profit made*. Again all the variables mentioned above have a positive relationship. An increase in Profit made leads to an increase of Dividends paid,

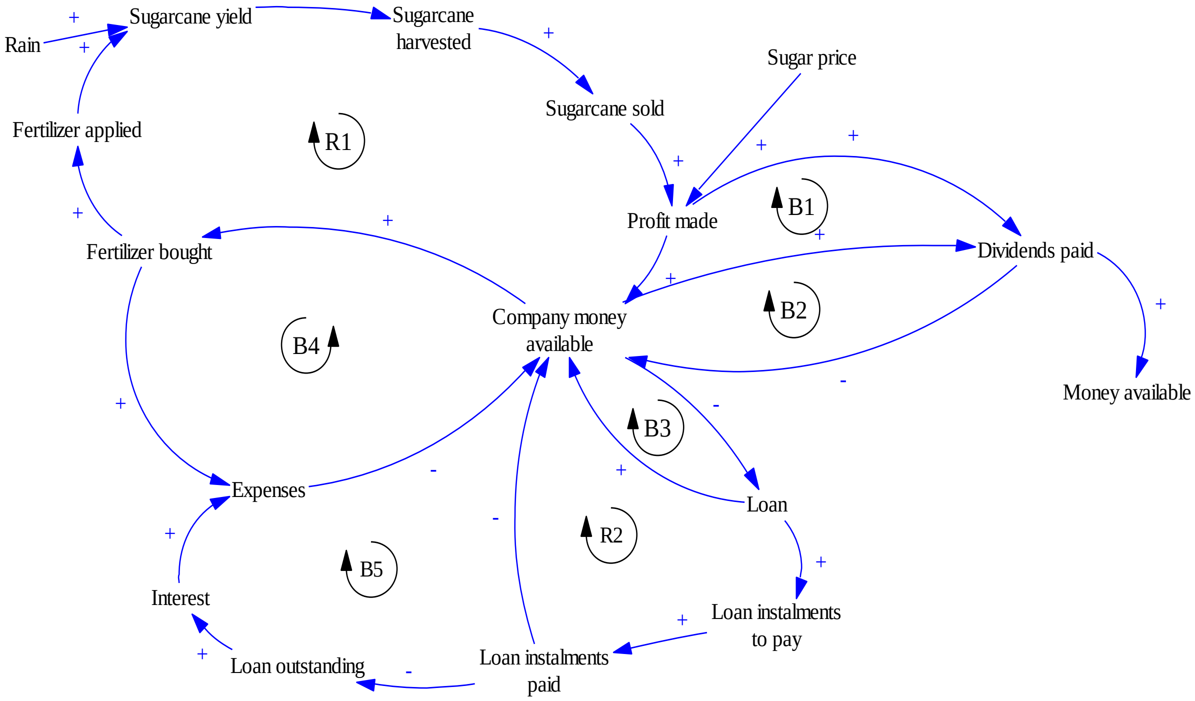

Figure 3-7: Industrial crops grown CLD

which then states that there will be less Company money available and are therefore a negative (-) relationship. Because of this last relationship, the whole feedback loop is considered balancing

The feedback loop R2 explains the impact of loan repayment on the amount of money the company has available. Whenever the company has got less money available, then more *Loans* will be needed. Therefore there is a negative (-) relationship. As the *Loans* increase, the number of *Loan instalments to pay* increase and therefore the number of *Loan instalments paid* also increases. Making the two relationships both positive (+). *Company money available* decreases as the more *Loan instalments* are paid and that is why the relationship is negative (-). This is an example of where an equal amount of negative (-) relationships forms a reinforcing (R2) feedback loop.

3.2.4 Food consumption CLD

The *Food consumption CLD* shown in Figure 3-8 describes the five reinforcing and four balancing feedback loops that interact to form the *Food consumption sub-model*. Three of the four food security pillars (described in **2.2**) can also be noted in Figure 3-8 namely; *Food* *stability*, *Access to food* and *Food available*. These three pillars are indicated by the variables *Money available* and *Calories available*. The variables *Livestock* and *Crops grown* are external variables for this model but are modelled in *Livestock kept* and *Crops grown* sub-models.

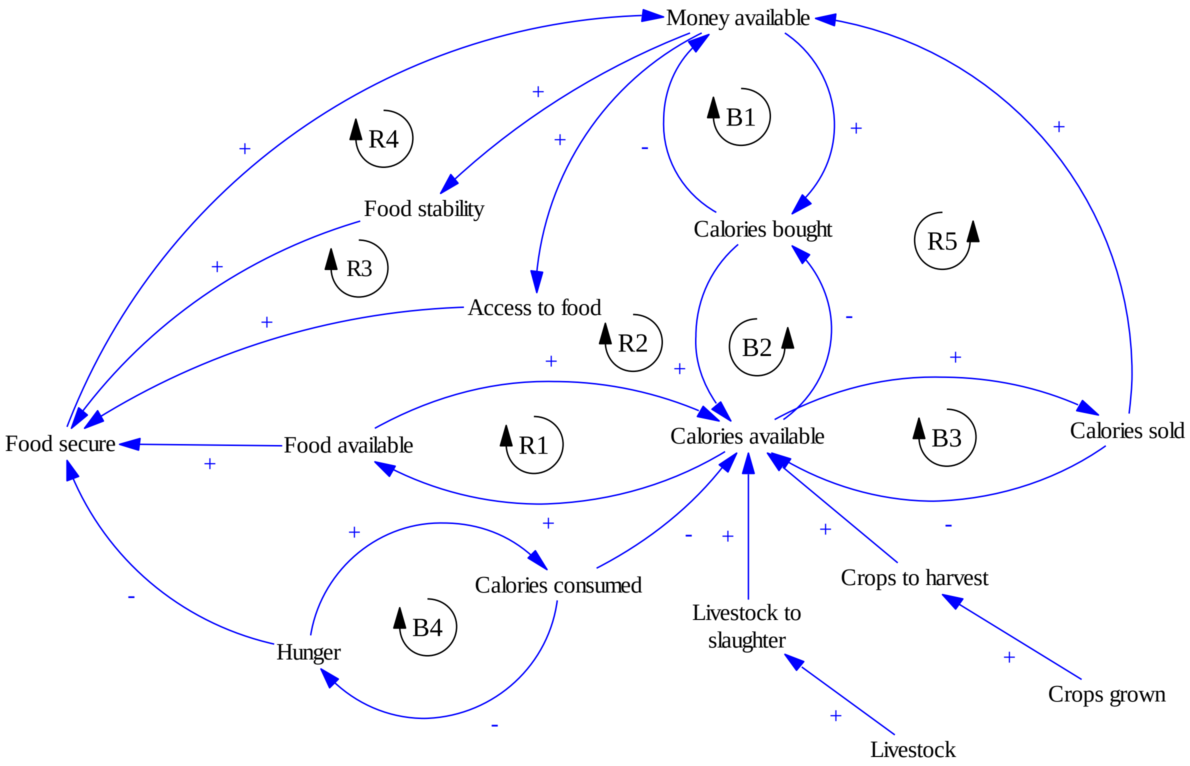

Figure 3-8: Food consumption CLD

All the feedback loops are equally important, but only B1, B2, R2 and R4 will be explained in more detail. For the balancing loops B1 and B2, Figure 3-8 shows that when there is more *Money available*, then more *Calories* will be *bought* which will lead to an increase in *Calories available*. Whenever there are more *Calories available* then fewer *Calories* will be *bought* and when fewer *Calories* are *bought*, then the household will have more *Money available*. That is why both those feedback loops are balancing.

R2 describes the same relationships from *Money available* to *Calories available* than that of B1 and B2. Thereafter it forms part of another feedback loop which illustrates that when more *Calories* are *available*, then more *Food* is *available*, making the relationship positive (+). When there is more *Food available* the household are more *Food secure* and when more *Food secure* they do not have to use all their *Money available* to buy food, so it will increase, resulting in another positive (+) relationship.

The last feedback loop to be described here is R4 which shows how money can help a household with *Food stability*. When a household has more *Money available* then they will be able to buy food anytime even if the prices go up. This will mean that there is more stability in terms of food in the house. Being more *Food stable* also increases the household's *Food security*. Then again as explained above, when a household is more *Food secure,* then they will have more *Money available*. Since all the relationships are positive (+) this feedback loop is reinforcing (R).

3.2.5 Crops grown CLD

Figure 3-9 illustrates the *Crops grown CLD*, which is a generic feedback loop that was used to construct the Crops grown SFD. Generic, because it explains the basic relationships and variables used in this sub-model, but is not crop specific. Four types of crops are modelled namely; dry maize, green maize, vegetables and groundnuts.

Three reinforcing and one balancing feedback loop form the *Crops grown CLD* shown in Figure 3-9. Being part of an IC company as well as *Rain* are external variables for this CLD. *Calories available* links this sub-model directly to that of *Food consumption*.

Feedback loops R1 and R2 will now be explained in more detail.

R1 describes the effect that money will have on buying fertilizer and how that will increase the yields. When more *Money* is *available*, then more *Fertilizer* can be *bought* which should lead to an increase in *Yield* and therefore a larger harvest. When more *Crops* are *harvested*, more *Crops* will be *available* and also more *Crops* can be *sold*. If more *Crops* are *sold* then more *Money* will be *available*. Since all the relationships are positive (+) this feedback loop is reinforcing.

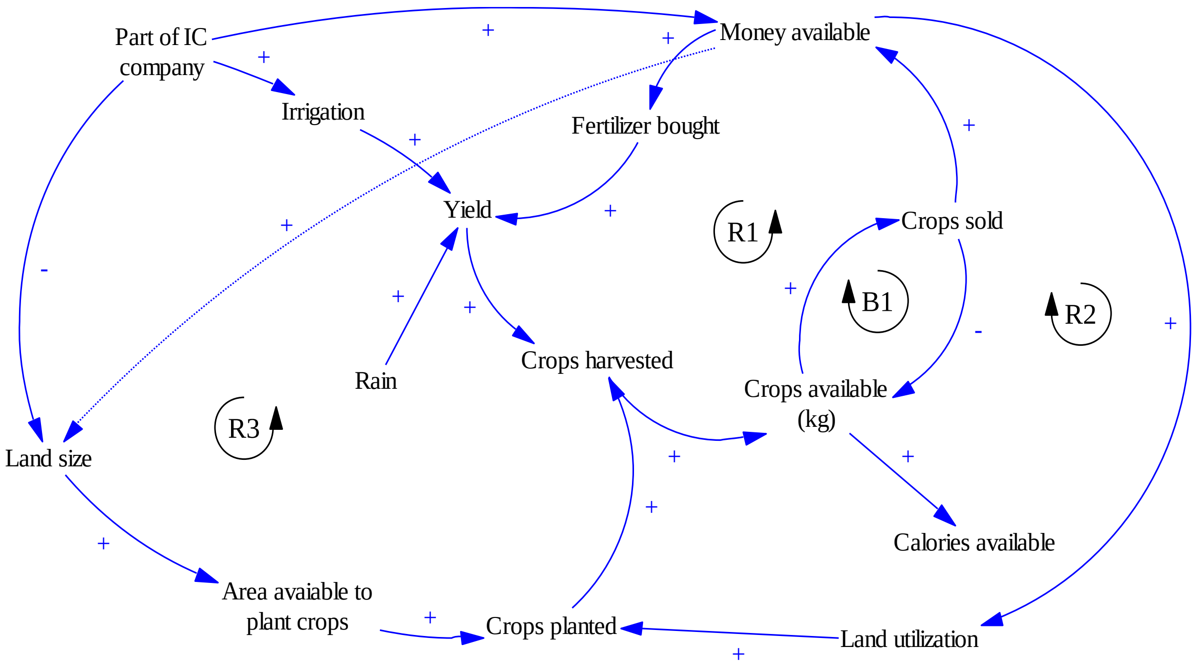

Figure 3-9: Crops grown CLD

Having more Money available should lead to better (more) Land utilization since the possibility of hiring implements and labour is great and inputs can be bought. When the land is better utilized, then more crops will be planted and therefore more crops harvested. From here R2 are similar to R1 with all the relationships positive (+).

3.3 Dynamic modelling

The following section provides a description of the six different sub-models used to simulate the impact of industrial crops on food security for Swaziland. The major stocks and flows of each model are described mathematically. In addition to that, the key variables and system dynamics are discussed. Assumptions that were made for each sub-model are also explained. The time frame that was chosen as explained in section **3.1.2** is from the year 2016 (t_0) to the year 2035 (t_n) thus making it 20 years, but the model is, however, run in months as shown in Table 3-1 First, the modelling structures will be explained.

3.3.1 Software used and simulation settings

The program used to model the impact of industrial crops on food security for Swaziland is called VensimPro which is part of Ventana systems inc. There are various modelling software packages on the market, but VensimPro was used, because the attended courses used VensimPro and therefore it is a more familiar package. Another advantage of using VensimPro is that there are many online resources and helplines available for the software.

The Euler method of integration is preferred over Runge-Kutta due to the level of uncertainty, speed requirements and lack of specificity-requirements (Musango, et al., 2015). A summary of the simulation settings that was set as the model was constructed can be seen in Table 3-1. These settings are applicable to all the sub-models described in section **3.3** and **Chapter 4**. The time step is set to 1 as shown in Table 3-1. It was originally set to 0.0625 in order to increase the integration accuracy, but the opposite proved to be true for the model and the explanation is that there are too many non-continuous variables which do not make sense when integrated with time steps of 0.0625.

Table 3-1: Summary of simulation settings

Software	VensimPro
Initial time (t_0)	2016
Final time (t_n)	2035
Time step	1
Time units	Months
Integration type	Euler

The model is run in months as many of the variables were seasonal within a year. As with most simulation models, the model built also needs a start-up period which in this case is one year.

Table 3-2 illustrates the different structures and their meanings/functions within the software. The table should help anyone unfamiliar with the software to be able to grasp the dynamics of any model built on VensimPro. All the sub-models built to simulate the impact of industrial crops on food security for Swaziland can be found in **Appendix A**.

Table 3-2: Vensim SFD modelling structures adapted from (Sterman, 2000)

Type	Meaning/Function	Identifier
Stock (Level)	Cumulative – Integral over difference in rates	$\boxed{\text{Level}}$
Flow (Rate)	Flow of material over time	Rate ⧖
Auxiliary	Model variable – defined by equations	Model variable
Constant	Independent (Can be changed by the modeller)	Name of constant
Shadow variable	Allows interlinking while maintaining order (Variable duplicity is not allowed)	<shadow variable>
Arrow	Delivers a variable for the use in the equation of another	→

3.3.2 CLD and stock and flow model integration

As explained in section **3.2**, most of the CLDs do integrate with one another and therefore integration within the different sub-models also takes place. The elements of each CLD that are presented within the six sub-models can be observed in Table 3-3. This is an indication of how dynamic the model is. Most of the CLDs integrate with more than one other sub-model. Both the *Food consumption* and the *Crops grown CLDs* integrate directly with three other sub-models. The *Livestock kept CLD* however is independent and only integrate with the economic stand sub-model. All other CLD and sub-model integration can be seen in Table 3-3.

Table 3-3: CLD and sub-model integration table

	Sub-models					
CLDs	Economic stand	Livestock kept	Industrial crops grown	Food consumption	Rainfall	Crops grown
Economic stand CLD	X	X	X	X		X
Livestock kept CLD	X	X				
Industrial crops grown CLD	X		X		X	
Food consumption CLD	X	X		X		X
Crops grown CLD	X			X	X	X

3.3.3 Economic stand sub-model

The first sub-model represents the amount of money each household has available (MA(t)) in the Tshaneni area. The sub-model consists of one stock called *Money available* and nine flow variables. Of the nine flow variables, three are inflow variables (income) and six are outflow variables (expenses). The three inflow variables are *Salary* (r_{sal}), *Livestock sold* (r_{lss}) and *Produce sold* (r_{pds}). The six outflow variables are *Fertilizer bought* (r_{fzb}), *Food bought* (r_{fdb}), *Labour costs* (r_{lbc}), *Water and pumping costs* (r_{wpc}), *Extra calories bought* (r_{ecb}) and *Investments made* (r_{inm}). (The equations for all the different inflow and outflow variables indicated in this chapter are explained in **Appendix C**.) Equation 3-1 represents the *Money available* variable and the effects that the different flows have on it over time.

Equation 3-1

$$MA(t) = MA(t_0) + \int_{t_0}^{t_n} [\mathrm{r_{sal}} + \mathrm{r_{lss}} + r_{pds} - r_{fzb} - r_{fdb} - r_{lbc} - r_{wpc} - r_{ecb} - r_{inm}]\, dt$$

Salary is influenced by *Education*, *Occupation* and whether someone is a shareholder of an IC company determines whether they will receive dividends. All possible Education and Occupation combinations are entered into multiple lookup tables as per the FICESSA data. The tables showing the relationships can be found in **Appendix D**. Salary, in this case, refers to all off-farm income. The variable *Livestock sold* is influenced by the *Livestock kept* sub-model which will be explained in section **3.3.4.** *Produce sold* is also influenced by a sub-model called *Crops grown* and the dynamics behind it is explained in **3.3.6**.

The amount of *Fertilizer bought* is influenced by the amount of *Money available* as well as the size of land planted. A test to check whether someone has enough money to buy the needed fertilizer is done first and if the results are negative, then someone will buy just as much as they can afford. *Food bought* is based on average buying habits of the people of Tshaneni according to the FICESSA survey data. So is *Labour costs* and *Water and pumping costs*.

The number of *Extra calories* bought variable is influenced by the number of *Calories available* as well as *Money available*. Every month the model test to ensure that there are enough Calories available for the current as well as the next month. Whenever there is not enough available, then a test will be done to see whether there is enough Money available to purchase the Extra calories needed for the next month. If this test also shows a negative result, then the household will use their remaining *Money available* to purchase as many Extra calories as possible. However if the test shows a positive result, then the number of *Extra calories* needed will be bought and added to the *Calories available*, as explained in section **3.3.7**.

The outflow variable *Investments made* indicates money that has been converted to some form of an asset which can be returned to cash when needed. It is, however, a small proportion of the amount of money available.

Money available is one of the indicators indicating how food secure a household is. The *Economic stand* sub-model and the dynamics and interactions of it can be seen in Figure A-0-1 in **Appendix A**.

Assumptions made for the Economic stand sub-model

- The initial amount of money ($MA(t_0)$) someone has is 0 so that everybody can be compared on the present and not let their past influence the model. The model also takes one year to start up, so the effect will be minimal.
- People do not save that much money, a big part of the money disappears.
- Inflation is not taken into account.
- People reinvest money in some form that could be used later (displayed as money, but could be assets that was bought).
- It is assumed that every household have three adults.

3.3.4 Livestock kept sub-model

The *Livestock kept* model represents the population of all four types of livestock modelled namely cattle, pigs, goats and chickens. Equation 3-2 is generic for all four types. *Livestock population* (LP(t)) (a separate one for each type) is the stock variable for this sub model. The stock has one inflow variable namely *Births* (r_{bir}) and two outflow variables, *Deaths* (r_{deh}) and *Livestock sold* (r_{lss}) which can be found in Equation 3-1 as well.

The inflow variable *Births* is influenced by a birth rate which differs for each type of livestock. The value, as well as the source for every birth rate, can be found in Table A-0-1 in **Appendix B**. (So can all other input variables and their values). *Deaths* are influenced by a death rate. The amount of *Livestock sold* is determined by a percentage of the livestock. It is important to note that the values of *Deaths*, *Births* and *Livestock sold* are modelled as integers.

Equation 3-2

$$LP(t) = LP(t_0) + \int_{t_0}^{t_n} [r_{bir} - r_{deh} - r_{lss}]\, dt$$

The value of the initial *Livestock population* (LP(t_0) is influenced by an individual's *Education* and *Occupation*, but can also be set to the average of the Tshaneni area. Livestock population is converted to either money when it is sold or to calories that influences the *Economic stand* and *Food consumed* models respectively. The structure and dynamics of the *Livestock kept* sub-model can be seen in Figure A-0-3 to Figure A-0-6 in **Appendix A**.

Assumptions made for the Livestock kept sub-model

- The limiting factor for herd size is the carrying capacity of the communal grazing land.
- Anybody can own livestock.
- People do not buy livestock for breeding.
- All types of livestock have the same death %.
- Births takes place once a year.
- Occupation & Education level determines the initial livestock (Only when scenarios concerning Occupation & Education levels are run).

3.3.5 Industrial crops grown sub-model

The *Industrial crops grown* model is illustrated in Figure A-0-7 in **Appendix A**. The model represents an FA's finances as they farm with IC. There are two stocks in this model, namely *Company money available* (CMA(t)) and *Loan outstanding* (LO(t)). The stock *Company money available* will be explained first. It consists of one inflow variable and four outflow variables. *Sugar harvest income* (r_{shi}) is the only inflow variable while *Expenses* (r_{exs}), *Replanting* (r_{rep}), *Loan payback* (r_{lpb}) and *Dividends paid* (r_{ddp}) are the outflow variables. Equation 3-3 illustrates the *Company money available* (CMA(t)) and the influence all the related variables have on it over time.

Equation 3-3

$$CMA(t) = CMA(t_0) + \int_{t_0}^{t_n} [r_{shi} - r_{exs} - r_{rep} - r_{lpb} - r_{ddp}]dt$$

The *Sugar harvest income* is dependent on the *Sugar price*, *Sucrose content*, *Sugarcane yield* as well as the *Sugar company farm size*. All the values for these variables can be found in Table A-0-1 in **Appendix B**. Expenses refer to the sugarcane operational cost which consists of *Haulage*, *Fertilizer*, *Electricity*, *Labour & admin*, *Overheads*, *Sugarcane irrigation* and *Chemicals & pesticides*.

Sugarcane has to be replanted every 5 to 10 years (Baucum, et al., 2015) to ensure the best yields and this cost is reflected through the variable *Replanting*. The variable *Loan payback* is self-explanatory and is dependent on the *Loan instalment*, the *Payback period* and the *Loan outstanding*. The outflow variable *Dividends paid* is the variable that will directly influence the *Economic stand* sub-model and therefore the household's food security. The value of the *Dividends paid* variable is determined through multiple variables and probabilities. Firstly a combination of the monetary *Pay-out point*, *Sugar price influence* and *Time to replant* is used to calculate the *Probability of a dividend payout*. Then this probability variable is combined with *Acceptable risk* and the *Percentage of profit* that will be paid out as dividends to calculate the *Dividend paid*. After this, the *Dividend* that is *paid* is divided by the number of shareholders to get the value each shareholder receives. The structure, as well as the dynamics behind the Industrial crops grown sub-model, is illustrated in Figure A-0-7 in **Appendix A**.

Initial Company money available (CMA(t_0)) is the amount that is left after the cost of machinery and initial preparation & planting costs are subtracted from the initial loan.

The second stock in this sub-model is *Loan outstanding* (LO(t)). It is made up out of a single inflow variable namely *Interest* (r_{int}) and also a single outflow variable named *Instalments paid* (r_{isp}). The impact that the in- and outflow variables have on the *Loan outstanding* over time is shown in Equation 3-4 below.

Equation 3-4

$$LO(t) = LO(t_0) + \int_{t_0}^{t_n} [r_{int} - r_{isp}]dt$$

The flow variable *Interest* is determined by the *Interest rate* and *Loan outstanding*. *Instalments paid* is directly linked to the flow variable *Loan payback* from Equation 3-3.

Assumptions made for the Industrial crops grown sub-model

- Loans were only granted at the beginning of the project.
- Replanting will happen every ten years.
- Loan repayments do take place as they should.
- Maintenance costs are negligible.
- Loan payback period of 10 years.
- Funds are managed as best as possible.

3.3.6 Crops grown sub-model

There are four main crops modelled in this sub-model. These crops include *Dry maize*, *Green maize* (standard maize, but harvested earlier), *Vegetables* and *Groundnuts*. Equation 3-5 shows the generic flow of the rates and variables for each of these four crops. There are four stocks (one for each crop but will be generalised to *Crops available* (CA(t)) for this explanation) that can be found in the *Crops grown* sub-model. The stocks each have two inflow variables and one outflow variable. The inflow variables include *Crops bought* (r_{cbt}) and *Crop yield* (r_{cyd}) while the outflow variable is *Crop sold* (r_{csd}). The sum of all the crops sold can be seen in Equation 3-1, while the sum of all the different crop yields is found in Equation 3-6 as well. Equation 3-5 below shows the maths behind the Crops grown sub-model.

Equation 3-5

$$CA(t) = CA(t_0) + \int_{t_0}^{t_n} [r_{cbt} + r_{cyd} - r_{csd}]dt$$

Crops bought is a variable that is determined by the average buying habits of the local people of Tshaneni and is based on the FICESSA survey data. The sum of all the different crops can also be found in the *Food consumption* sub-model.

For the *Crop yield,* many different variables are taken into account. The variables include *Trend between rainfall and yield*, *Fertilizer impact, Irrigation, Rainfall, Average plot size, Plot utilization* and area that each crop is planted as a percentage of the utilized plot.

The *Trend between rainfall and yield* indicates the effect that rain has on the yield and forms a parabolic shape with a max of 975mm (for maize) after which the yield will start to decrease again (Oseni & Masarirambi, 2011). Additional to the rainfall and yield trend, the *Fertilizer impact* is also taken into account but this is represented by a limit to which it strives (Crista, et al., 2014). There comes a certain point where more fertilizer will not cause a better yield, but it will rather stay constant. The other variables that determine the value of *Crop yield* are self-explanatory.

Amount of *Crops sold* is based on averages from the FICESSA survey data.

All values for variables can be seen in Table A-0-1 in **Appendix B**. The structure and dynamics of the Crops grown model are also shown in Figure A-0-8 to Figure A-0-10 in **Appendix A**.

Assumptions made for the Crops grown sub-model

- When irrigation is applied, then it will be equivalent to 975mm of rain which will ensure max yield.
- Everybody who plants maize has access to the subsidised maize seed and fertilizer packages.
- When someone is part of an FA/IC company then they will utilize 100% of their smaller piece (30m x 30m block) of available land to plant crops.
- When someone is not part of an FA/IC company then they will only utilize 70% of their piece of land.
- Only water and fertilizer has an influence on yields.
- Only the four main crops are grown.

3.3.7 Food consumption sub-model

Only one stock variable is found in the *Food consumption* sub-model namely *Calories available* (CAL(t)). This variable is one of the two variables measured to indicate how food secure a household is. In total four inflow and three outflow variables influence *Calories available*. *Livestock calories* (r_{lsc}), *Calories grown* (r_{csg}), *Calories bought* (r_{csb}) and *Calories bought to fill up* (r_{cbf}) are the inflow variables, while *Loses* (r_{los}), *Calories sold* (r_{css}) and *Calories consumed* (r_{ccd}) are the outflow variables. Equation 3-6 points out how the variables interact over time.

Equation 3-6

$$CAL(t) = CAL(t_0) + \int_{t_0}^{t_n} [r_{lsc} + r_{csg} + r_{csb} + r_{cbf} - r_{los} - r_{css} - r_{ccd}]dt$$

The variables *Livestock calories*, *Calories grown* and *Calories bought* are all the sum of their separate models (explained in this chapter) but converted to calories. The structure and logic behind the *Calories bought to fill up* are explained in section **3.3.3**.

Amount of *Losses* is based on the paper *Assessment of rodent damage to stored maize (Zea mays L.) on smallholder farms in Tanzania* from Mdangi, et al. (2013). The paper investigated the amount of food losses due to rodents (mainly rats). Therefore a certain percentage of

Losses is taken into account for this model. *Calories sold* is determined through the FICESSA survey data. *Calories consumed* is calculated by multiplying the *Average household size* by the number of *Calories needed per person* not to be hungry. All the values for the variables can be found in Table A-0-1 in **Appendix B**. The structure and dynamics of the *Food consumption model* can also be seen in Figure A-0-11 in **Appendix A**.

Assumptions made for the Food consumption sub-model

- People do not store their maize and food in completely isolated areas or bins (Used to determine losses due to pests).
- Expired food is taken into account in the *Losses*.
- That months have 30 days.
- Calories are the only measure (nutrients, variety and vitamins are excluded).

3.3.8 Rainfall sub-model

The *Rainfall* sub-model does not have a stock variable, but rather just variables for each month that are based on historical rainfall data. The distribution is random and includes the minimum, maximum, mean and standard deviation for each month. The structure of the model can be seen in Figure A-0-12 in **Appendix A** and all the values in Table A-0-1 in **Appendix B**.

Assumptions made for the Rainfall sub-model

- The cumulative rain during October, November, December, January, February and March determines yield outputs.

3.4 Testing, scenario planning and modelling

This section describes the tests that need to be done to ensure confidence in the model. Next, it explains the different scenarios that are used to fully comprehend the influences that the variables have on one another as well as how the feedback loops react to different inputs.

Each scenario will, therefore, be run and tested and the results thereof will be discussed in Chapter 4.

3.4.1 Testing

To use a model for policy analysis or scenario testing it should first be tested to gain confidence in the model as well as the model results. To achieve this level of confidence model validation and sensitivity analysis should be done (Maani & Cavan, 2012). Maani & Cavan (2012) is also of opinion that a single test is not sufficient to test a model, but rather that confidence is gained through doing more tests. Forrester & Senge (1980) argue that *"as a model passes more tests and as new points of correspondence between the model and empirical reality are identified"* confidence in the model accumulates. Therefore, a combination of tests should be used to validate the model. Finally, Sterman (2000) agrees that a model cannot be validated using a single test.

SDM validity can be categorised into two main categories; *structure validity* and *behaviour validity*. *Structure validity* has two components namely, *direct structure tests* and *structure-orientated behaviour tests*. *Direct structure tests* determine the validity of the model by comparing it directly to knowledge of the real system structure. S*tructure orientated behaviour tests* perform behaviour tests on model simulation patterns and in such a way determines the validity of the model indirectly (Barlas, 1996). According to Vlanchos, et al. (2007) the two most common tests for *structure-orientated behaviour tests* are *extreme-condition* and *sensitivity analysis* tests.

After the *structure validity* tests are done and enough confidence in the model is gained, then the *behaviour validity* can be tested. The main aim of these tests is to test how accurately the model's behaviour relates to the real system patterns (Vlanchos, et al., 2007). Barlas, (1996) points out that the words *pattern prediction*, rather than *point prediction*, is very important to note when doing the *behaviour validity* tests.

Whenever historical data exists, then it should be used to validate the model. It can be used to prove that the model behaves like the real system (Sargent, 2013). There is however no historical data available for this specific area and therefore the historical data validation test cannot be done.

Maani & Cavana (2012) suggest a set of guidelines/steps that can be used to validate and build confidence in a system dynamics model. The steps are listed below.

1. CLD must correspond with the problem being modelled.
2. Equations, including signs in equations, must correspond to the CLD.
3. The model must be dimensionally valid.
4. The model behaviour must be plausible.
5. The model should maintain a correct flow of "data".

3.4.1.1 Guideline tests

The first step to validate the model is to follow the guidelines/steps suggested by Maani & Cavana (2012). The first step is to determine whether the CLD corresponds to the problem at hand. The *Economic stand CLD* shown in Figure 3-3 illustrated the expanded CLD for the model and takes all the sub-models into account. It incorporates three of the four pillars of food security and also takes into account the farming of different commodities and ICs. It includes health, education and effects of rain and fertilizer as well. Therefore it can be said that the

Economic stand CLD corresponds to *The Impacts of industrial crops on food security in Swaziland: A system dynamics modelling approach* model.

The second step to validate the model according to Maani & Cavana's (2012) guidelines is to analyse if all the stock and flow diagram equations' signs match that of the corresponding CLDs. This was done for all the main stock and flow variables that are found in the CLDs as well and the result was that they all matched. An example of this is from the Crops grown CLD shown in Figure 3-9 where it indicates that if the amount of *Fertilizer bought* increase, then the *Yield* will also increase. Comparing this to Equation 3-7 that shows *Yield* from the *Crops grown* sub-model, it can be seen that this is true.

Equation 3-7

$$Yield = Plot\ utilization\ \%\ x\ Average\ plot\ size\ x\ Area\ of\ crop\ planted\ \%$$

$$x\ Fertilizer\ impact\ x\ Trend\ between\ rainfall\ and\ yield\ x\ Irrigation$$

It shows that when the other five variables stay constant and *Fertilizer impact* increase, then the yield will also increase.

Step 3 of the guideline is to ensure that the model is dimensionally valid. This means that the dimensions of all the variables on the right-hand side of the total equation should match the dimensions on the left-hand side. VensimPro has a function that tests the whole stock and flow model's dimensions and it returned *Units are A.O.K.*

The fourth step is to ensure that the model behaviour is plausible, thus that the model returns realistic values. This include tests to see that certain values only go to zero and not into the negative. All relevant tests were done and the model returns no unrealistic values and plausible behaviours.

The last step that Maani & Cavana (2012) suggest to validate a system dynamics simulation model is to ensure that the model maintains a correct flow of "data". This means that all the values that enter the model should be accounted for and none should be lost. The model should, therefore, maintain *conservation of flow*. There are a total of 12 stock variables as described in section **3.3**. All 12 stock variables were tested and each of them maintained *conservation of flow*.

3.4.1.2 Direct structure tests

As explained in section **3.1.3** mediated modelling was used as a data gathering process, but at the same time, it was used as a direct structure test to validate the model. During the time of research two field trips to Swaziland took place in order to consult with experts, extension officers from SWADE and locals who are involved with the KDDP project. Initially, the problem was identified and CLDs, as well as stock and flow models, were constructed. Then the logic behind them was tested by going through them with all the different groups mentioned above and whenever it was felt that the logic does not make sense or that the model misinterprets something, then it was changed. This was done till all the groups agreed that structurally the relationships and links make sense. This process helped to validate the model.

The second direct structure test involved the presentation of the model step by step to a panel of experts at a FICESSA meeting on the 16-20th of October 2017 in London. The panel included Dr. Alexandros Gasparatos (lecturer at University of Tokyo), Professor Katherine Willis (Director of science at Royal botanic gardens, KEW), Dr. Steve Wiggins (Principal Research Fellow at ODI (Overseas development agency)), Dr. Graham von Maltitz (CSIR research group leader for global change and ecosystems dynamics) and Dr Marc Macias-Fauria (lecturer at the University of Oxford) to name a few. The people mentioned above are all experts in their respective fields. Suggestions were made by them and were implemented and validated.

3.4.1.3 Extreme-condition test

These tests are conducted through increasing or decreasing variable values to the extreme in order to compare the results, test whether they are plausible and whether the system behaved like how the real problem would. If this proves true then it would increase the validity of the model a lot. It is however argued that humans struggle to anticipate complex system dynamics and behaviour under random operating circumstances. According to Vlachos, et al. (2007) it is easier for humans to anticipate the extreme circumstances of a complex system.

Multiple extreme-condition tests were conducted analysing model variables such as *crop yield (for each of the four)*, *average plot size*, *fertilizer impact, rainfall, salary, livestock sold, livestock births, calories sold, losses, IC expenses and sugar price*. Unfortunately, no historical extreme-condition data for that area was available to test the results found.

An example of one of the tests is that of the *sugar price*. The price of sugar was reduced 5 times from E2979 to E595.8 per ton. Under these extreme conditions, no dividends were received, as the FA was unable to make a profit and therefore unable to pay a dividend. This lead to the household not having enough *Calories available* (they could still grow a bit of crops on their 30m x 30m block) to feed themselves as well as no *Money available* to buy the needed extra calories. This is definitely a feasible result for the given reduced sugar price.

Another example is that of *losses*. The number of *losses* was increased to 90% of the calories that were available. This caused the number of *Calories available* to decrease drastically, which in turn meant that the household had to buy the maximum amount of food that they could afford to fill up their *Calories available*. This lead to a household without money and in most of the months without food. The results for this scenario is very plausible and turns out as expected.

All the other extreme-condition tests done also proved feasible results and turned out as expected, therefore it can be concluded as successful validation tests.

3.4.1.4 Sensitivity analysis

The aim of sensitivity analysis is to identify the parameters to which the model are extremely sensitive. It is also a test to determine whether the sensitivities makes sense in the real system that is modelled (Vlachos, et al., 2007). According to Maani & Cavana (2012), some initial parameters, conditions and relationships between variables are estimated during model construction owing to the lack of information. For this reason, a sensitivity analysis is performed on certain variables to understand how the model will behave when uncertain variables are verified.

The variables expected to be sensitive are the main variables that were assumed during the model development phase. They are primarily the different elasticities (variables that can change) in the model. The changes in the behaviour of one variable when another's relative value is changed is represented by the elasticities. Models are also expected to be very sensitive to initial values which in this case can be represented by *initial livestock, initial crops available, initial money available* and *initial loan value*.

Figure 3-10 and Figure 3-11 represent a sensitivity analysis test that was done to test the model's sensitivity to that of the *Initial cattle* of a household. This variable represents the number of cattle a household has to start with. It was found that the amount of *Money available*, as well as the number of Calories available, was very sensitive to the *Initial cattle* value.

It is expected that these variables will be very sensitive to the number of cattle, especially the number of *Calories available*. The reason for this is because there have been many debates regarding whether the people of Swaziland use their livestock (especially cattle) as food or whether they only see them as assets or a "bank" (store of wealth). One of the papers regarding it by Doran, et al. (1979) explains that people from Swaziland see livestock as a source of wealth and therefore do not consume it as food which leads to overgrazing. Through the model, it was also realised that it is very sensitive to whether people consume the livestock as food or see it as a store of wealth.

Figure 3-10 shows the spread of value of *Money available* of a household when the amount of *Initial cattle* is normally distributed with a minimum of 0 and a maximum of 15. It shows that there will be a bigger impact for the first 10 years after which the impact will still be apparent, but less.

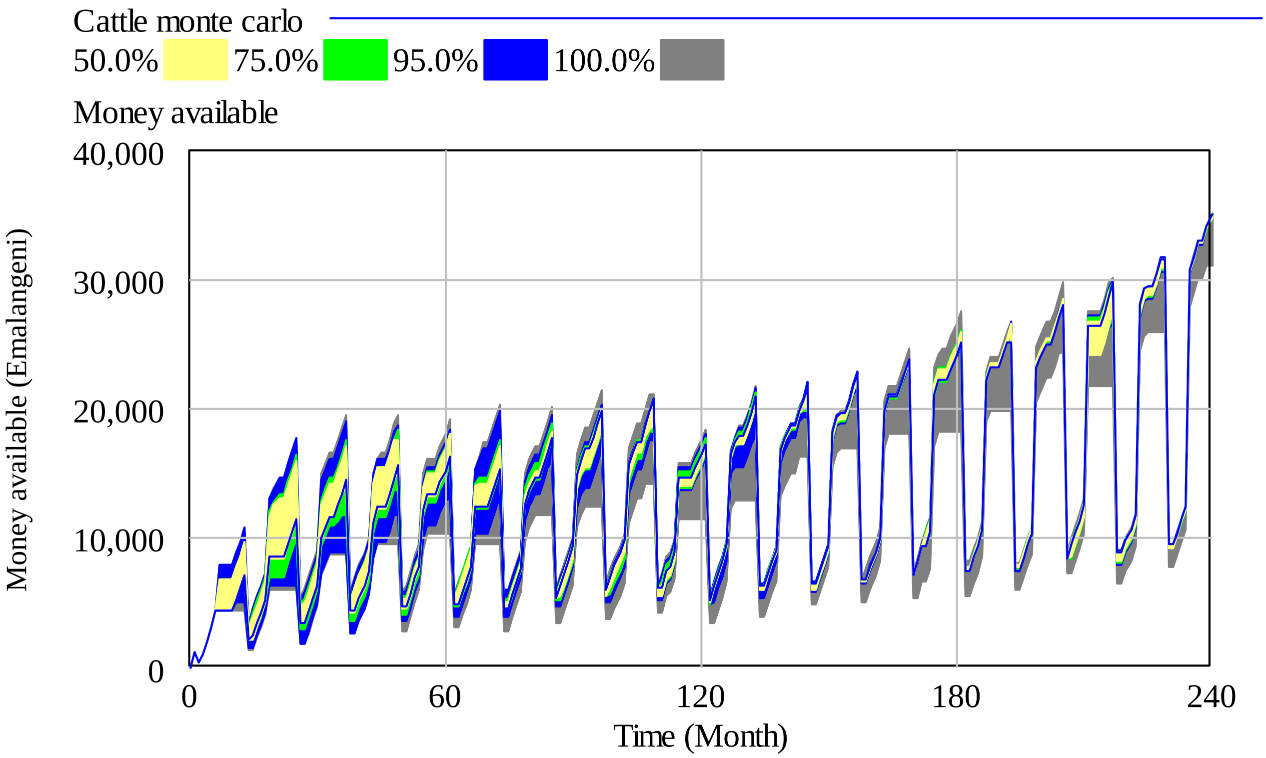

Figure 3-10: Cattle Monte carlo - Money available

It can also be seen in Figure 3-11 that the impact will be bigger during the first ten years. In addition it shows that the amount of *Initial cattle* has an exponential effect on the number of *Calories available*. The effect on the number of Calories bought to fill up is large as well, but not shown here. Another variable that also caused high sensitivity (small change to input has large change to output) for these variables is that of the *Initial sugar price*.

The results from the sensitivity analysis tests turned out as expected and were, therefore, a good validation for the model and its elasticities.

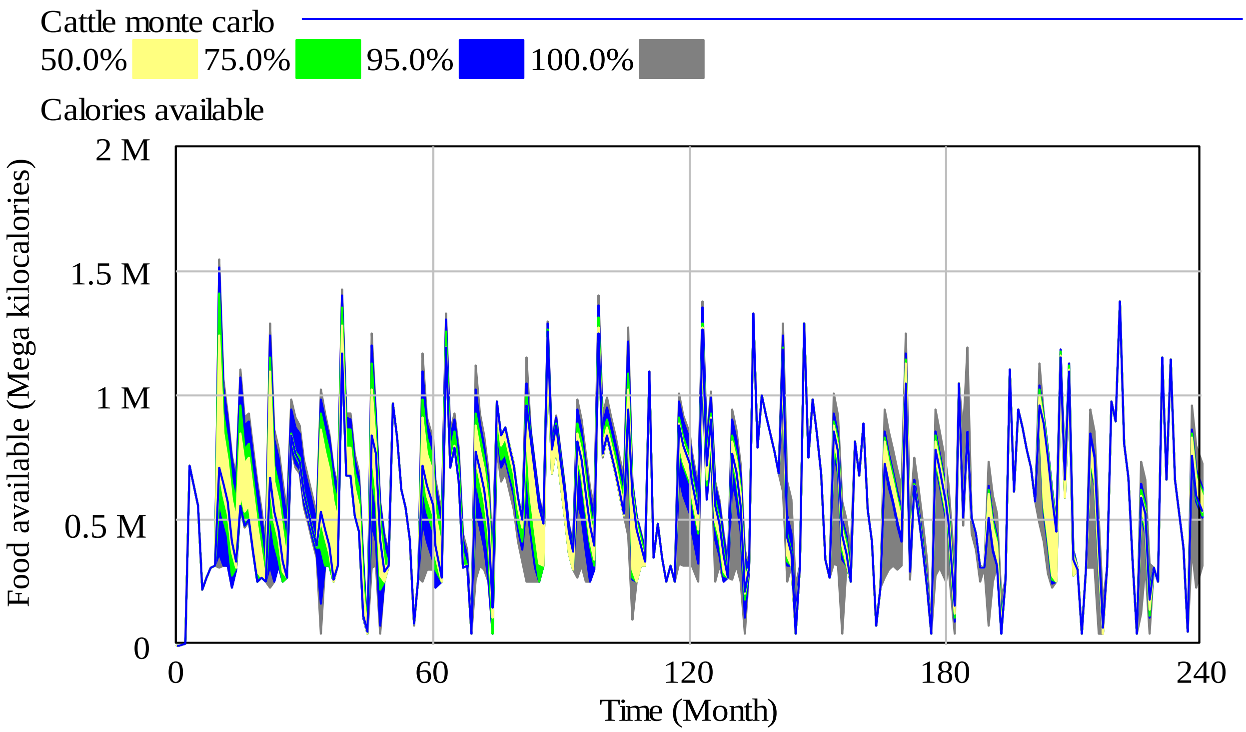

Figure 3-11: Cattle Monte carlo - Calories available

3.4.1.5 Validation summary

Table 3-4 shows a summary of all the validation tests that were done. The table lists the tests that were done, which elements were tested and then concludes on the results of the tests. Overall the model is validated through the tests that were done and therefore enough confidence is gained in the model to run scenarios and have valid results from them.

Table 3-4: Model validation summary

Test type	Elements tested	Conclusion
Guideline tests	Whether CLD corresponds to the problem that was modelled and if equations, as well as their signs, matched that in the CLDs. Tested the dimensional validity of the model and if the model returns realistic values. Finally, the behaviour was tested and the *conservation of flow*.	The model fulfilled each of the guideline tests and operation was realistic.
Direct structure tests	The validity of the model structure and its feedbacks and whether it represents the real system that is being modelled.	A number of experts validated the model structure and had input as to where changes had to be made.

Extreme-condition tests	crop yield (for each of the four), average plot size, fertilizer impact, rainfall, salary, livestock sold, livestock births, calories sold, losses, IC expenses and sugar price	The model behaved as expected under the extreme conditions.
Sensitivity tests	All initial variables and elasticity variables, but those that proved the highest sensitivity on *Money available* and *Calories available* were Initial cattle and *Initial sugar price*.	The model is more sensitive to certain of the variables than others but performed as expected.

3.4.2 Scenario planning

The scenarios are planned in such a way that most interactions will be tested and compared. Scenarios are used because for a problem like this, there is no one correct answer, but rather many positive and many negative influences which should be displayed through the results of the model.

The scenarios that will be run are:

- Base scenario (The average employed person in the area)

When an SD model is built and different scenarios are tested, then a base scenario is needed to compare other scenarios with. The base scenario represents the average case. This scenario describes the typical employed person in the Tshaneni area. The person is part of an average sized household in that area that is 5.33 people, according to the FICESSA survey data. This person also earns the average E1295/month salary of an employed person in the area. The scenario also describes someone who has his/her own plot of land in the area and plants a combination of dryland maize, vegetables and groundnuts and have a few livestock in terms of cattle, goats, pigs and chicken.

- IC company shareholder

The scenario describes someone who has joined an FA and therefore receives dividends from the sugar company of which he/she is a shareholder. The person also has got a 30m by 30m block around his/her house where maize, vegetables and groundnuts are grown. Even though it is illegal to irrigate this block, it is still done by most of the people, since they have the irrigation available now because of the sugar cane. This scenario is tested and compared to the base scenario.

- Climate variability scenario

An important dynamic that was noticed through the research is how people or households react to shocks and survive them. Therefore this scenario test to see how people who are part of an FA compare to people who are not part of one when a long-term drought comes. The scenario models that only 50% of the standard rain is received and the influences that a long-term drought like that will have on a few different types of households. The households will be compared and it will be observed whether people who are involved with ICs can handle shocks like that better than those not involved.

- Types of households compared

An average household is not something that will be found easily, therefore different household compositions will be compared to one another in this scenario. The end means of this scenario is again to test whether households who are involved with ICs are better off than those not involved.

- Influence of Education and occupation on food security

It was found when analysing the FICESSA survey data that education does play a role in terms of someone's food security status, but just through analysing the data it could not exactly be pinned down. Therefore this scenario compares households with the heads of the house having different education levels as well as different occupations. This scenario might help some policy questions regarding the importance of education in Swaziland and whether it might be used to fight food insecurity.

3.5 Conclusion: Modelling methodology

Method 1 form section **2.5.6** was chosen and used to structure this chapter as well as the following chapter. This chapter therefore started by explaining the problem and the boundaries and time frame for the model. How the data was gathered is also explained. An in-depth discussion as well as visual communication of all the relevant CLDs was done in order to illustrate the structure by which the model is built. The types of relationships between the main variables are indicated. All the major stocks and flows in the model are discussed in this chapter. The mathematical equations behind them and which variables are dependent on which are explained. Model testing and validation are done and discussed next. The validation of a model is an extremely important part of system dynamics modelling and the model proved to be validated and enough confidence was gained in order to run some scenarios. Next, the scenarios were planned and the reasoning behind each one are discussed. In total five scenarios was identified.

The next chapter discuss and represent the results graphically from each of the five scenarios that were run. Observations from the results are explained, but not analysed.

Chapter 4 : Modelling results

As described in section **2.5.6**, *Scenario planning & modelling* is the fourth phase of system thinking and modelling. The scenario planning was done in section **3.4.2** but now the scenarios will be simulated. This chapter, therefore, discusses the results of all the different scenarios that were run. The main indicators that are used to indicate the food security of a household are *Money available, Calories available and Calories bought to fill up*.

The model scenario input parameters are discussed and quantified for every scenario. After that, the model is run with the different input parameters in order to obtain results for the scenarios which are then discussed and compared to one another.

4.1 Base scenario

The base scenario portrays the typical employed person in Tshaneni as explained in section **3.4.2**. The person who is the head of the house will earn the average salary of E1295/month as shown in Table 4-1. The household size is 5.33 people, which is the average for the area. The head of the household is not part of an IC company and plants vegetables and crops on 70% of his/her 3-hectare plot that does not have any irrigation. Certain livestock is also kept and the normal weather is simulated. Table 4-1 below shows the main variables and their values as well as units for the *Base scenario*.

Table 4-1: Variable values for Base scenario

Variable	Value	Unit
Occupation	Not specified	
Education	Not specified	
Salary	1295 (= 1295 South African Rand)	Emalangeni (E)/Month (Swaziland currency)
Household size	5.33	Person
Plot size	3	Hectare
Irrigation	No	
Part of IC company	No	
Plot utilization	70	Percent (%)
Rain	Normal	mm
Calories needed	2085.5	Kilocalorie/person

The two variables used to indicate a household’s food security state are *Money available* and *Calories available*. Additionally, *Calories bought to fill up* is also relevant, as it shows when a household had to buy food with the *Money available* in order to have enough *Calories available* to eat. Figure 4-1 shows the amount of money that a household will have available to buy food or fill any other needs like tuition fees with. At the end of twenty years, a Base scenario household would have accumulated E31800, which is not a lot of money for twenty years of work, but at least the household are able to stay food secure.

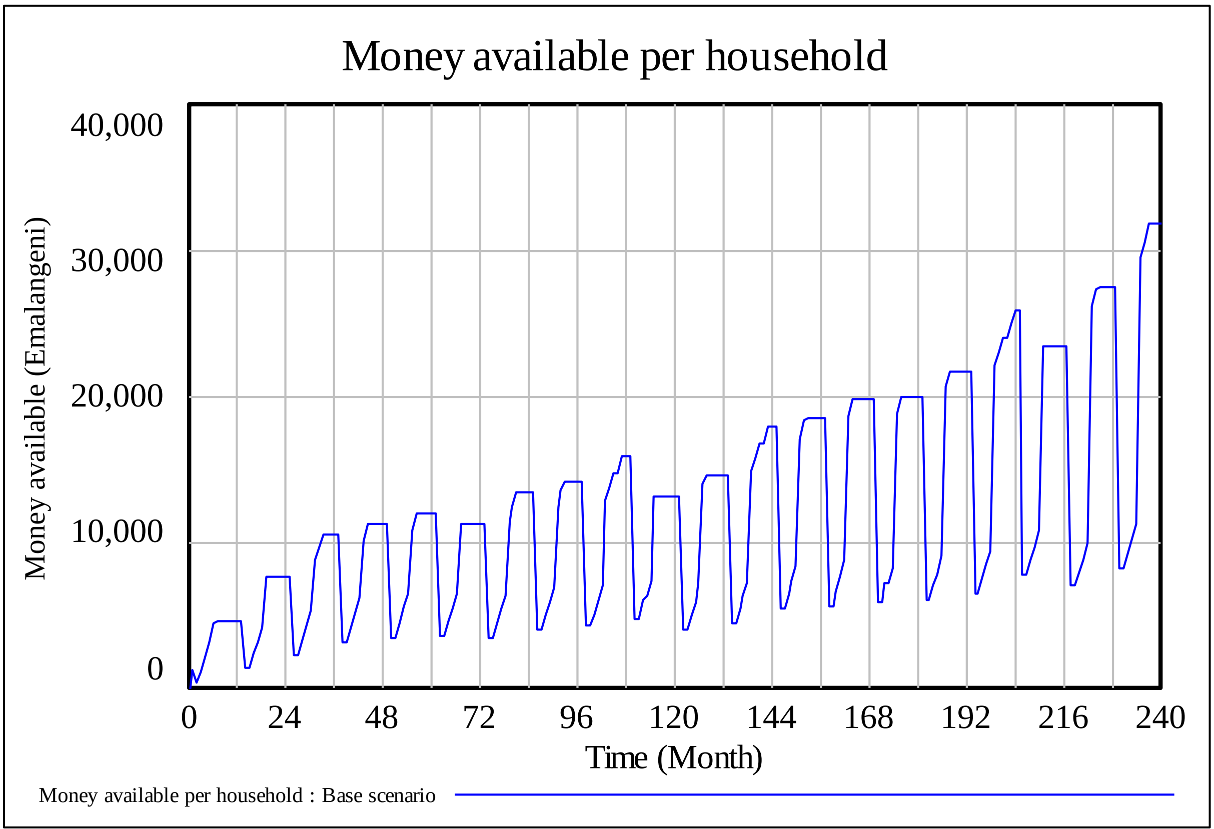

Figure 4-1: Base scenario - Money available

The amount of Calories available over time for the household is shown in Figure 4-3. It can be noted that the Calories available spike once every 12 months when they harvest the crops. It is also clear that for most years it goes to an absolute minimum just before harvest time. In addition Figure 4-3 shows that the Base scenario household is food secure as they always have enough *Calories available* to consume.

Figure 4-2 illustrates the number of calories that had to be bought to fill the gap between production and consumption, whenever there were one. This variable is a good indicator to see whether people stay food secure through purchasing or producing food for themselves. The maximum amount a household will buy at a time is 383 525 kilocalories (this include a 15% buffer, as the actual needed calories are 333 500 kilocalories) because that is the amount they will need for the current and next month.

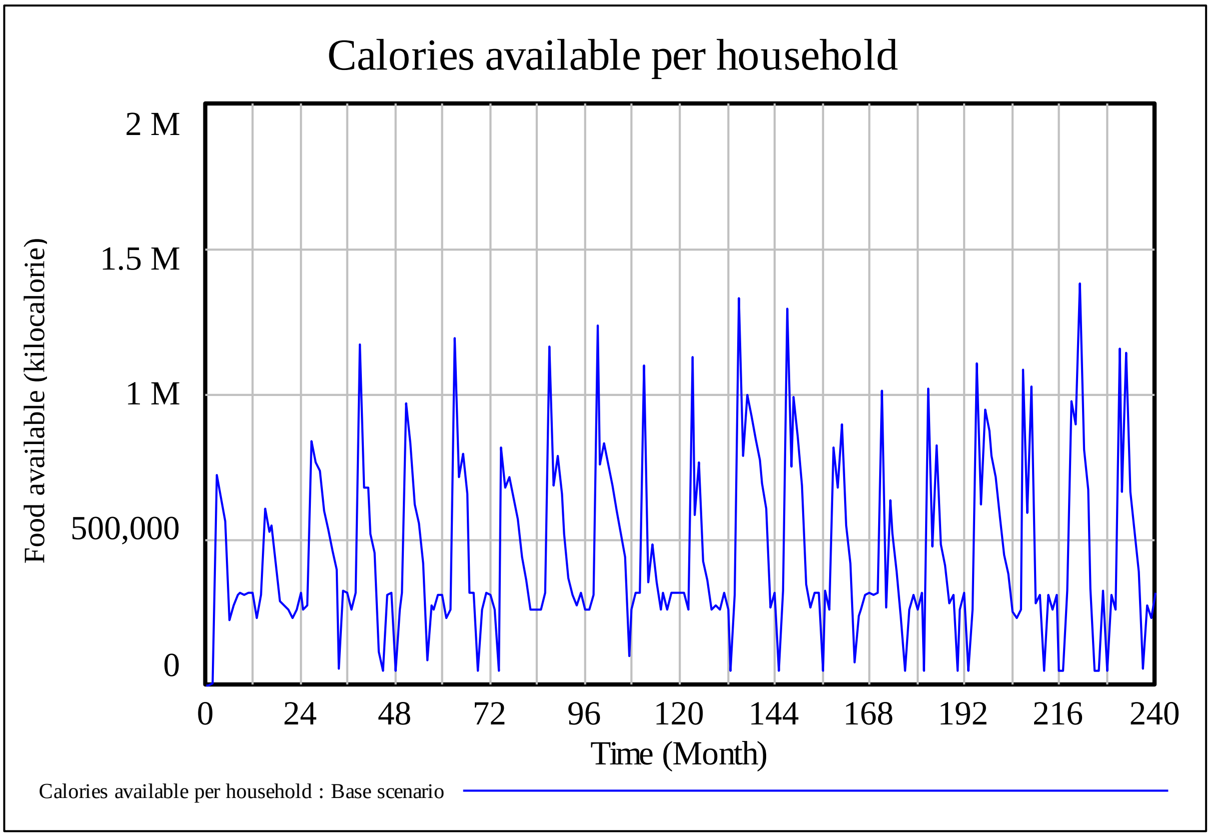

Figure 4-2: Base scenario - Calories available

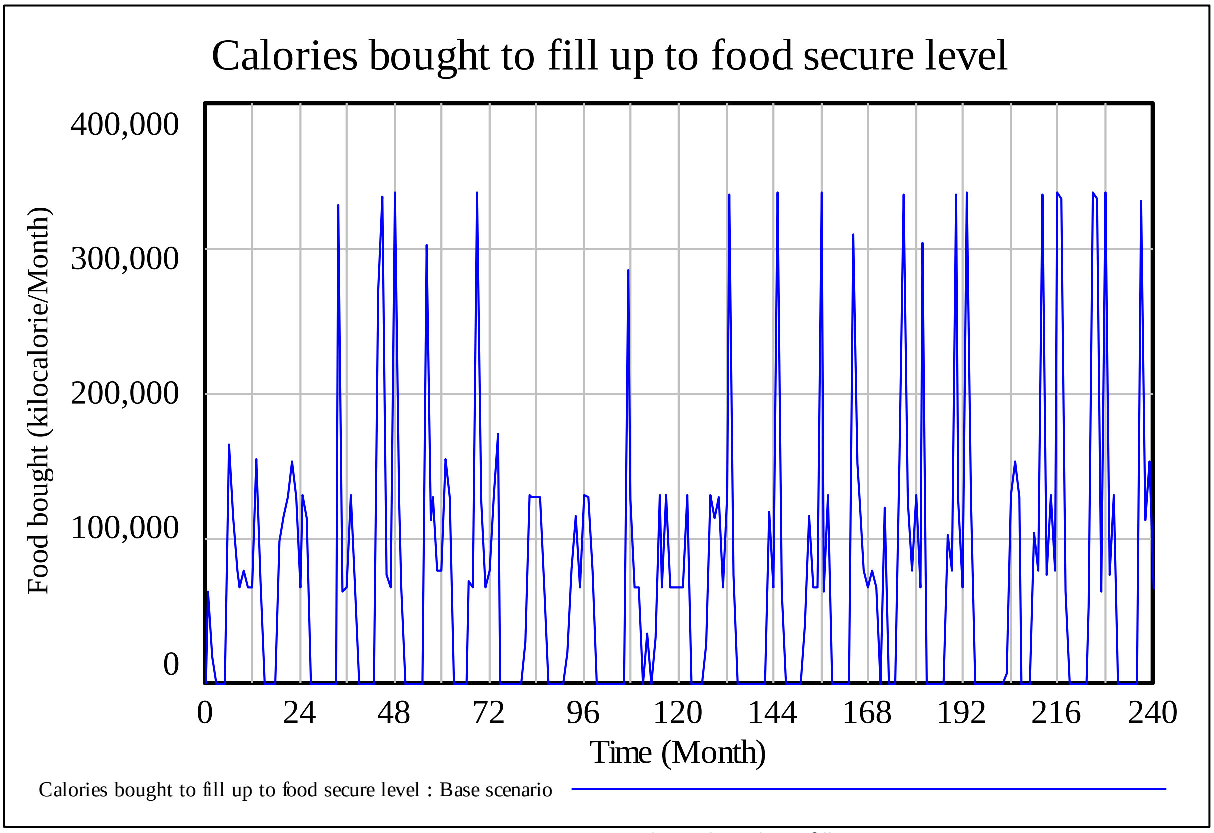

Figure 4-3: Base scenario - Calories bought to fill up

4.2 IC company shareholder

The IC company shareholder scenario is very straightforward as it compares someone who is part of an IC company directly with the average person in Tshaneni. This person will not have a big salary (E761/month as shown in Table 4-2) as he/she will mainly be dependent on the dividend that will be received. The piece of land available to plant crops is also much smaller than that to which a household in the base scenario has access to, therefore it would be easier to fully utilize the plot. The yields should be higher because of the irrigation as well.

Table 4-2: Variable values for IC company shareholder scenario

Variable	Value		Unit
Scenario	**Base**	**IC company shareholder**	
Occupation	Not specified	Not specified	
Education	Not specified	Not specified	
Salary	1295	761	Emalangeni/Month (Swaziland currency)
Household size	5.33	5.33	Person
Plot size	3	0.09	Hectare
Irrigation	No	Yes	
Part of IC company	No	Yes	
Plot utilization	70	100	Percent (%)
Rain	Normal	Normal	mm
Calories needed	2085.5	2085.5	Kilocalorie/person/day
Receive dividends	No	Yes	Emalangeni

Figure 4-5 illustrates that a household who is an IC company shareholder will most of the twenty years have more capital available. It is also interesting to note that there will only be a gap of E310 after the twenty years between the available money for the households in this scenario. (IC company shareholder household will have more.) In addition Figure 4-5 shows that a household who is an IC company shareholder's *Money available* will fluctuate a lot more than that of the average household, but will, in general, be in a better state.

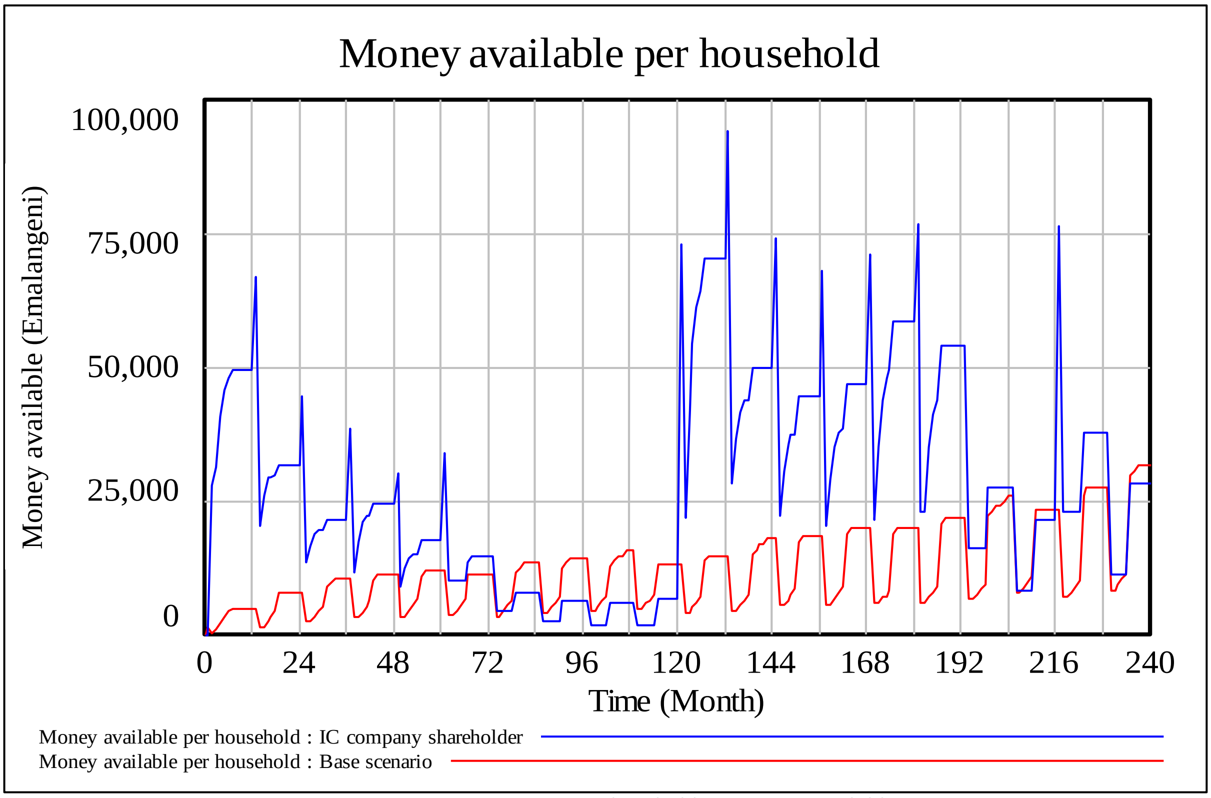

Figure 4-5: IC company shareholder - Money available

Figure 4-4 compares the number of Calories available for consumption to each household. The red line that represents an average household in the area is in most cases just above the blue line, which means that they will have slightly more food available, but as learned from Figure 4-5 they will have less money available. This state is still a very good state to be in, in terms

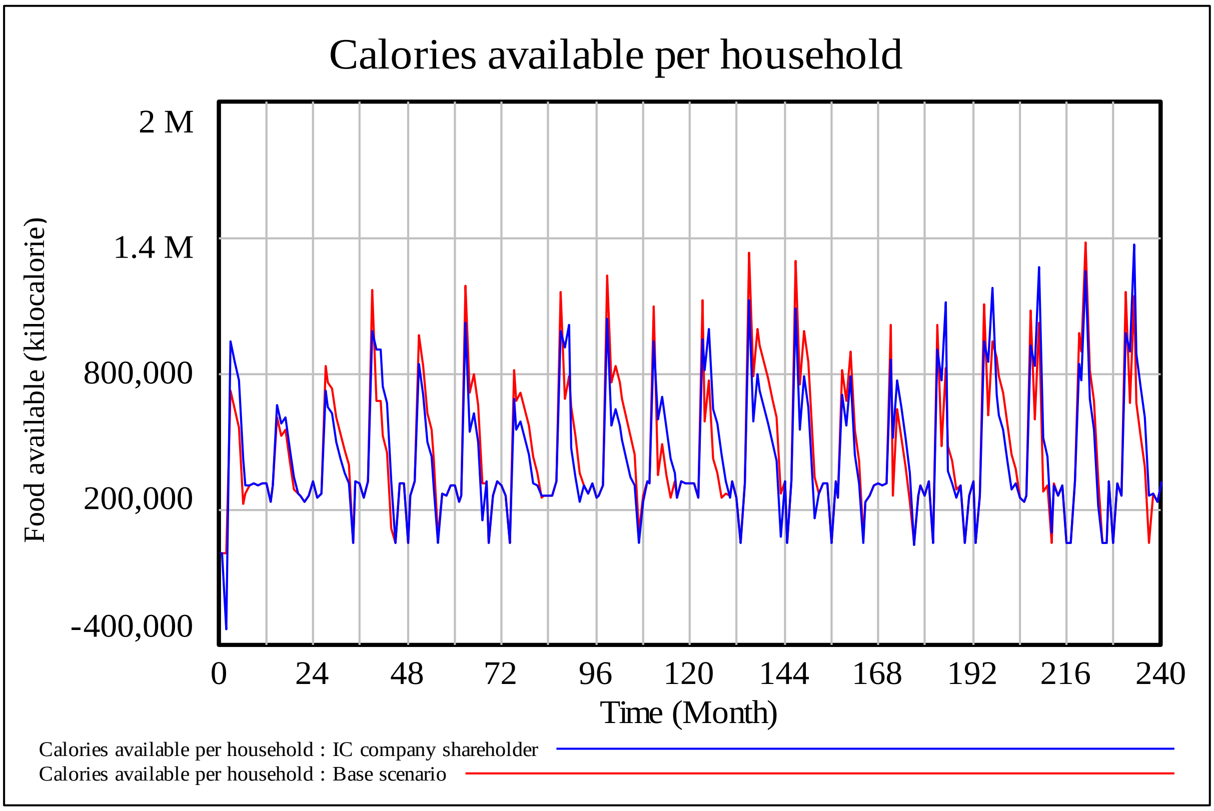

Figure 4-4: IC company shareholder - Calories available

of food security, as both households are food secure. In total, the IC company shareholder household had only the 15% buffer *Calories available* for 18 months of the twenty years, while the Base scenario household had the 15% buffer *Calories available* for 17 months of the twenty years. It, therefore, implies that they had to buy the maximum amount of calories for 18 and 17 months respectively as shown in Figure 4-6 below. It is also prominent that the household who is an IC company shareholder buys more food in that the average household.

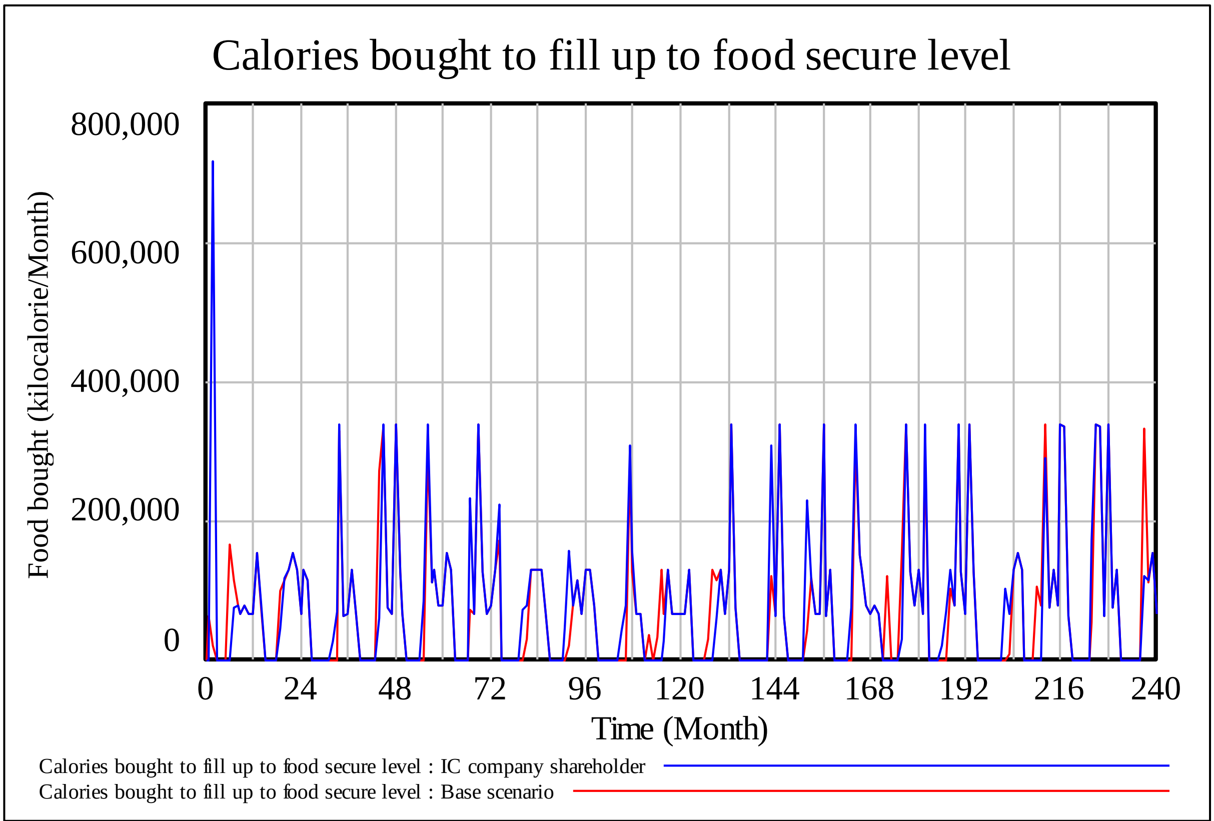

Figure 4-6: IC company shareholder - Calories bought to fill up

4.3 Climate variability scenario

The Climate variability scenario is compared to the previous two scenarios as shown in Table 4-3. The only difference between this scenario and the Base scenario is that only 50% of the rainfall is received. Table 4-3 below shows all the other main variables for the three different scenarios.

Table 4-3: Variable values for Climate variability scenario

Variable	**Value**			**Unit**
Scenario	**Base**	**IC company shareholder**	**Climate variability scenario**	
Occupation	Not specified	Not specified	Not specified	

Education	Not specified	Not specified	Not specified	
Salary	1295	761	1295	Emalangeni/Month (Swaziland currency)
Household size	5.33	5.33	5.33	Person
Plot size	3	0.09	3	Hectare
Irrigation	No	Yes	No	
Part of IC company	No	Yes	No	
Plot utilization	70	100	70	Percent (%)
Rain	Normal	Normal	50% of normal	mm
Calories needed	2085.5	2085.5	2085.5	Kilocalorie/person
Receive dividends	No	Yes	No	Emalangeni

When comparing the amount of *Money available* for the three scenarios in Figure 4-7 it is clear that for most of the twenty years a household that is an IC company shareholder will have more *Money available* than the other households in this scenario. The Climate variability scenario household barely had enough money to buy food (thus almost no money for anything non-food) in the first five years, but was able to recover after that.

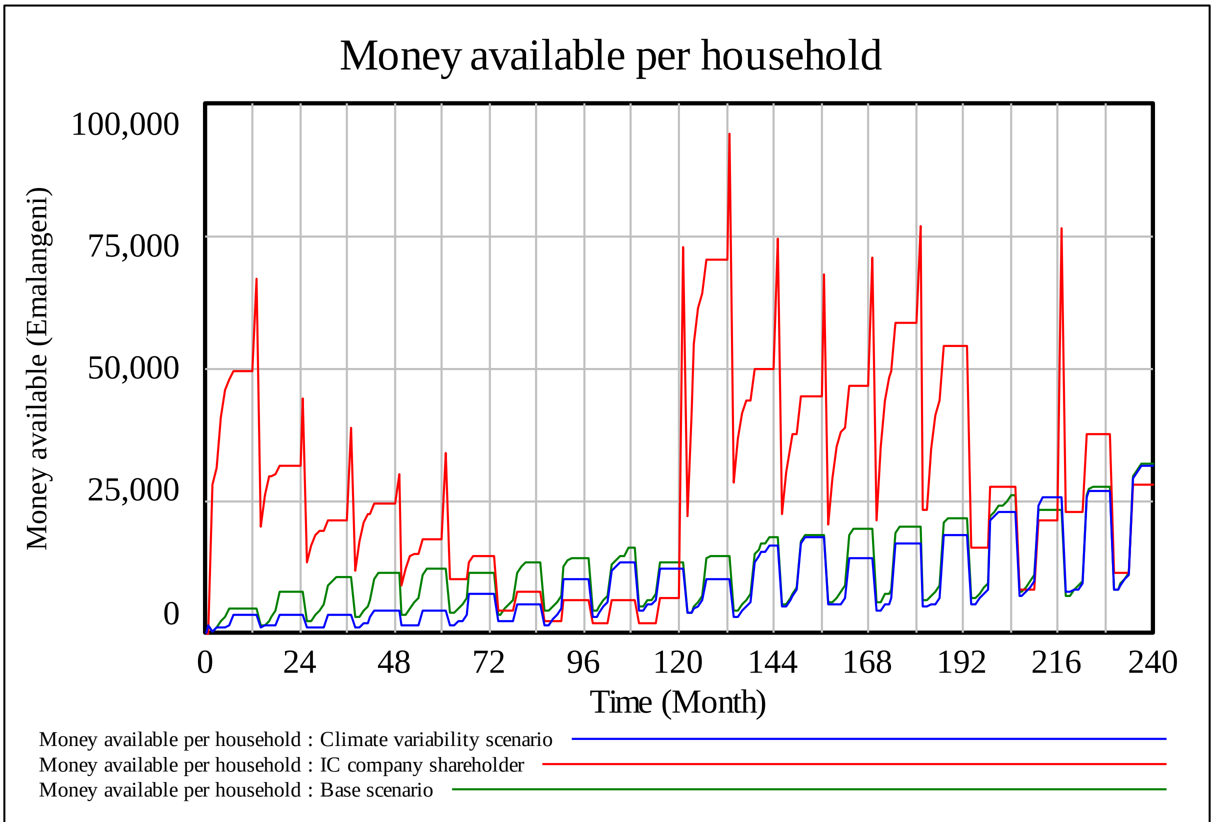

Figure 4-7: Climate variability scenario - Money available

Figure 4-8 is a clear indication that a prolonged drought will be unfavourable to the average household. There are at least three times in the first five years that the specific household will not have enough *Calories available* to eat. There are interesting coping methods behind situations like that. Most times other people in the community will take care of a household that struggles like this, but then again this represents the average household, therefore most households will not be food secure in a prolonged drought like the one simulated, unless irrigation schemes can be expanded to all plots.

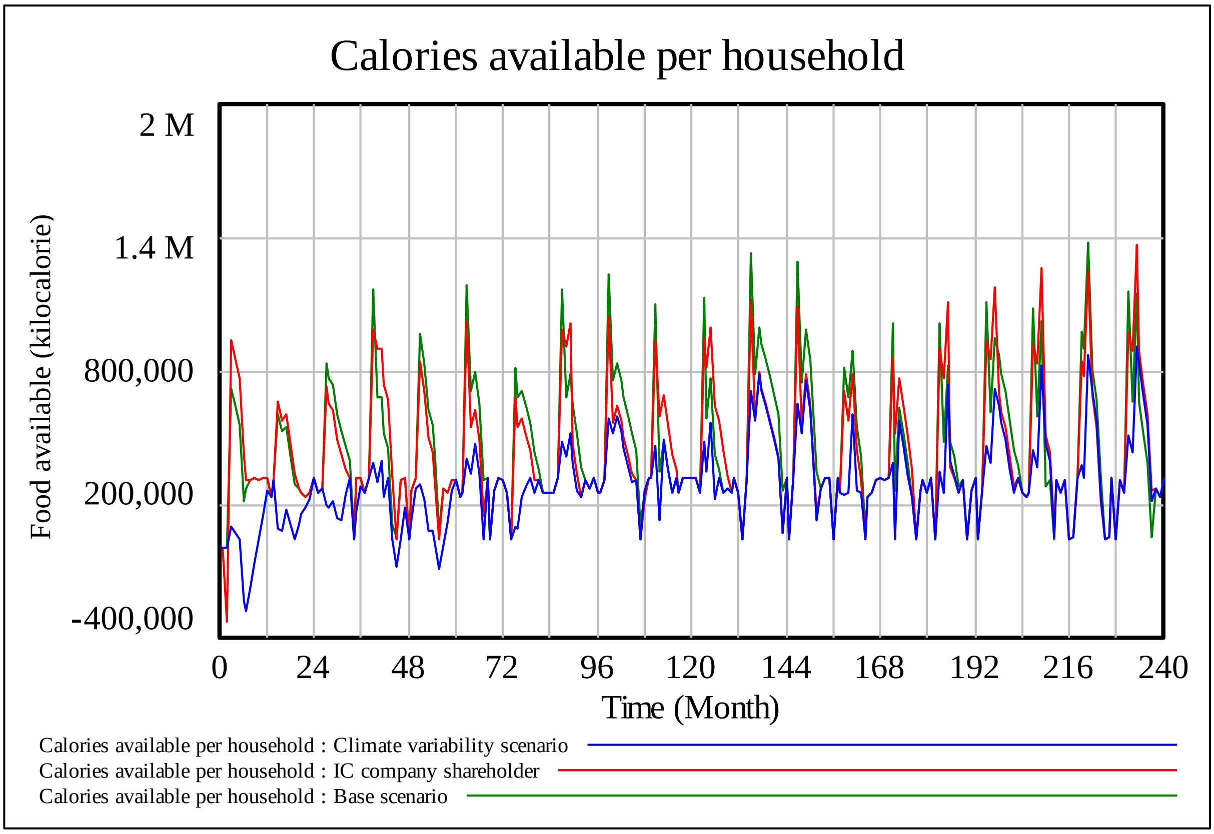

Figure 4-8: Climate variability scenario - Calories available

Figure 4-9 illustrates that the Climate variability scenario household really had to buy lots of Calories because of the fact that their yields were so low, if they even had yields. Then again Figure 4-7 shows that there were not any money to buy food in the first five years. The household bought the maximum amount of calories 14 times in the twenty years and if there were enough Money available during the first five years, then there would have been at least an additional four times. Through Figure 4-9 it is evident that the average household in Tshaneni will not be food secure during a prolonged drought.

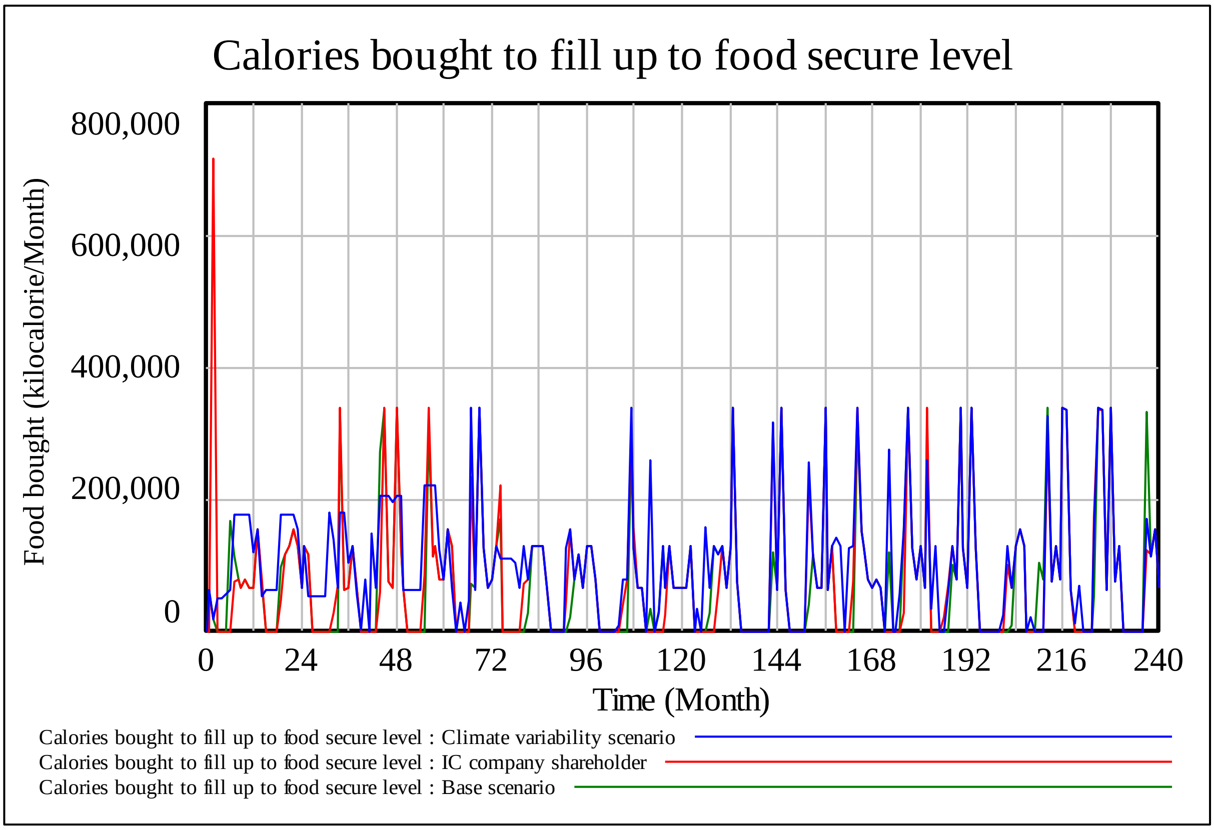

Figure 4-9: Climate variability scenario - Calories bought to fill up

4.4 Types of households compared

The fourth scenario compares 6 different typical types of households in the Swaziland context. The types of *Occupation* and *Education* seen in Table 4-4 refers to that of the head of each household. The six different types of households include that from the first two scenarios, namely the average (Base) household and the household who is an IC company shareholder. Additionally, it includes households with the head being self-employed, a civil servant, a farmer and a sugar company employee (being on the board of an FA). Each of these household heads has a unique *Education* level as indicated in the third coulomb of Table 4-4. An important variable to notice is that of the *Household size*. The average *Household size* for the area is 5.33 people per household, but for this scenario the aim was to compare real households with one another, therefore choosing integer values for most of the household sizes. The last variable to notice is that of the plot utilization percentage. It stays 100% for a household that is an IC company shareholder and 70% for the average household any all the other, except for the one where the head of the household is a farmer. The reasoning behind this 90% utilization is twofold. Firstly because farming is the head of the household's occupation, therefore, he/she will have more time for planting and work on the plot and secondly, because the household consist of one person more than the average household, which therefore means more labourers to work the land.

Table 4-4: Variable values for Types of households compared scenario

Variable	Value						Unit
Scenario	**Base**	**IC company shareholder**	**Self-employed person as head**	**Civil servant as head**	**Farmer as head**	**Sugar company employee as head**	
Occupation	Not specified	Not specified	Self-employed	Civil servant	Farmer	Sugar company employee	
Education	Not specified	Not specified	Some secondary school	No formal education	Finished secondary school	Finished primary school	
Salary	1295	761	636.40	2777	629	5312	Emalangeni/Month
Household size	5.33	5.33	4	5.33	6	6	Person
Plot size	3	0.09	3	3	3	3	Hectare
Irrigation	No	Yes	No	No	No	No	
Part of IC company	No	Yes	No	No	No	No	
Plot utilization	70	100	70	70	90	70	Percent (%)
Rain	Normal	Normal	Normal	Normal	Normal	Normal	mm
Calories needed	2085.5	2085.5	2085.5	2085.5	2085.5	2085.5	Kilocalorie/person

Receive dividends	No	Yes	No	No	No	No	Emalangeni

Figure 4-10 shows a few interesting results. Firstly it shows that being an IC company shareholder is still the most profitable or at least for the first 18 years after which it becomes more profitable being on the management team of an IC company. The third best household to be a part of considering profitability is one where the head is a civil servant. For the first 7 years being part of a farming household that has one more person in the house is by far the worst. Being self-employed or just part of the average household lies in between.

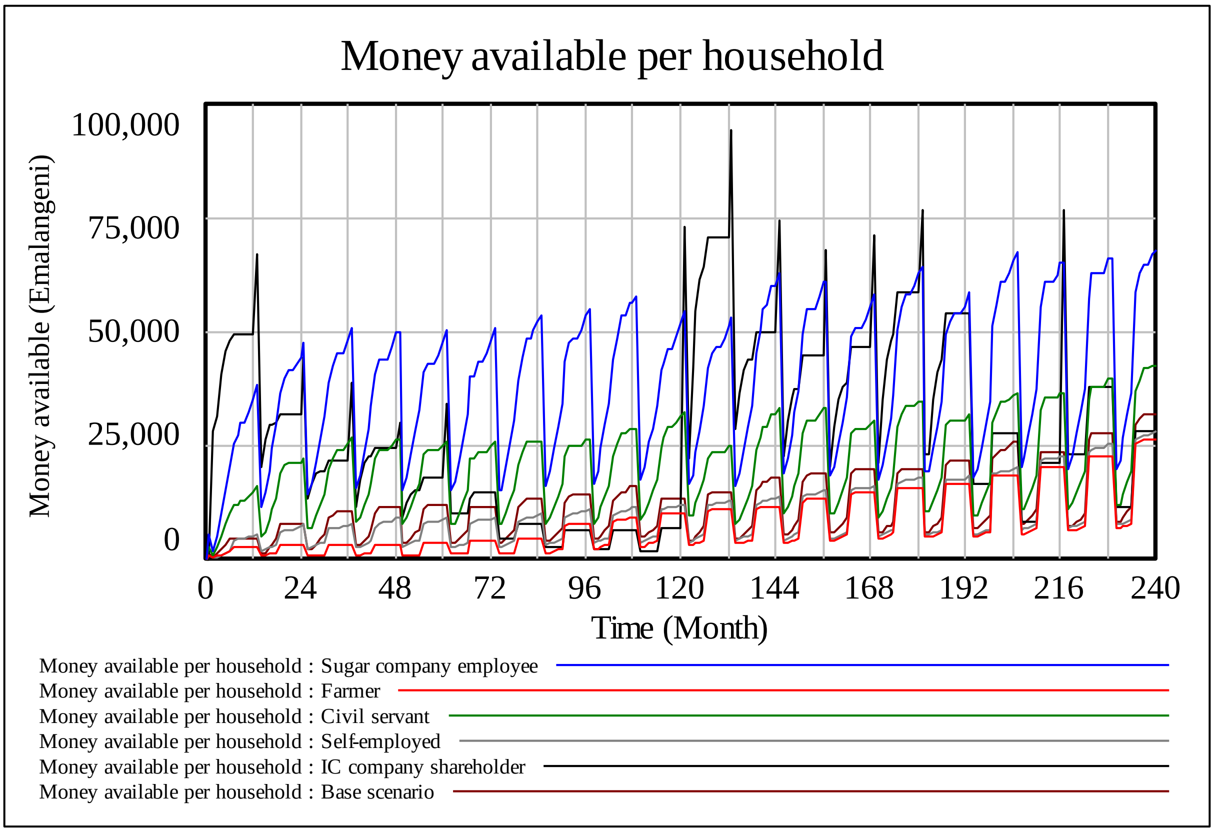

Figure 4-10: Types of households compared - Money available

Figure 4-12 illustrates that from the six different types of households it is the worst being a farming household, or at least for the first 80 months, as the number of *Calories available* turns and stays positive for the first time then. Having *Calories available* go negative means that the specific household had no food available and had to make alternative plans to find food. In most cases, the alternative plan would be to be reliant on family and friends, which means that at some time these calories will have to be returned, therefore the number of *Calories available* can go into the negative.

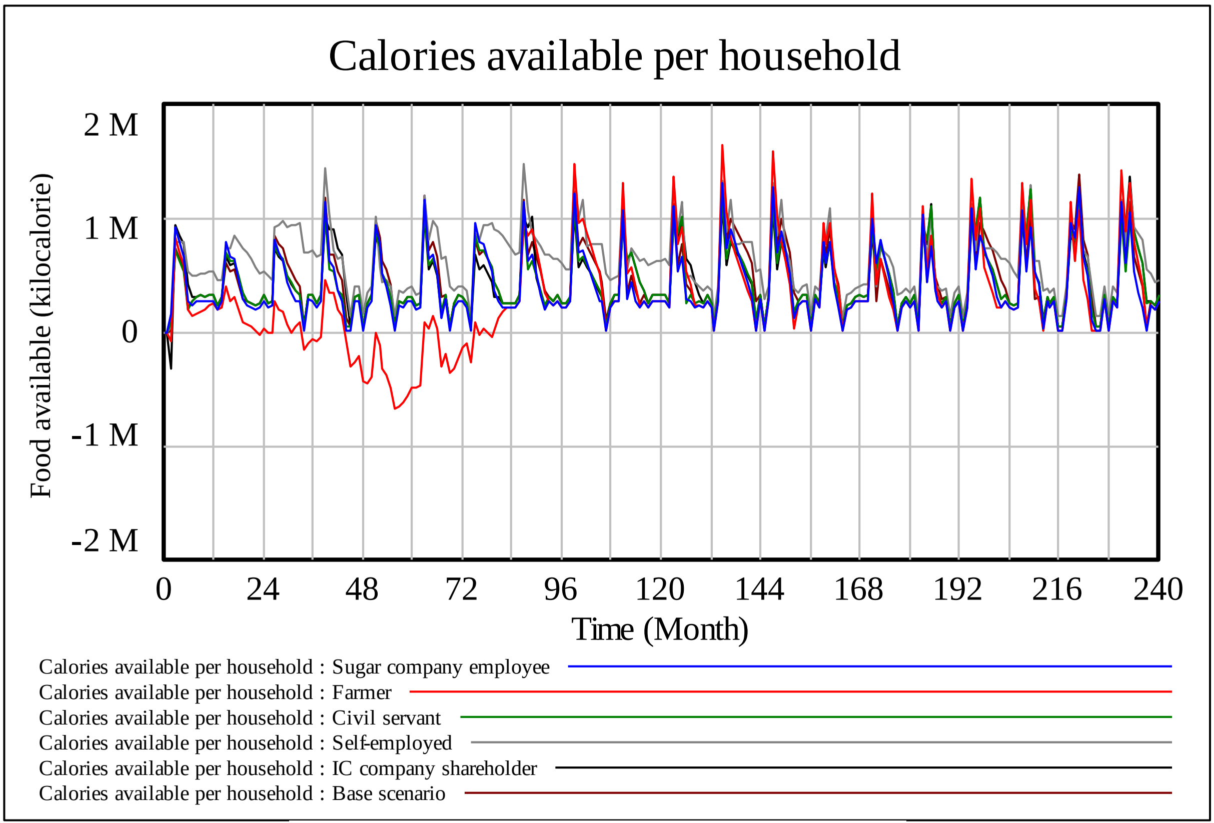

Figure 4-12: Types of households compared - Calories available

Even though being a farming household with 6 members are the worst position to be in for the first 80 months (6 years and 8 months), after then a farming household will constantly have the most calories available of all the households. Being a self-employed household is the only

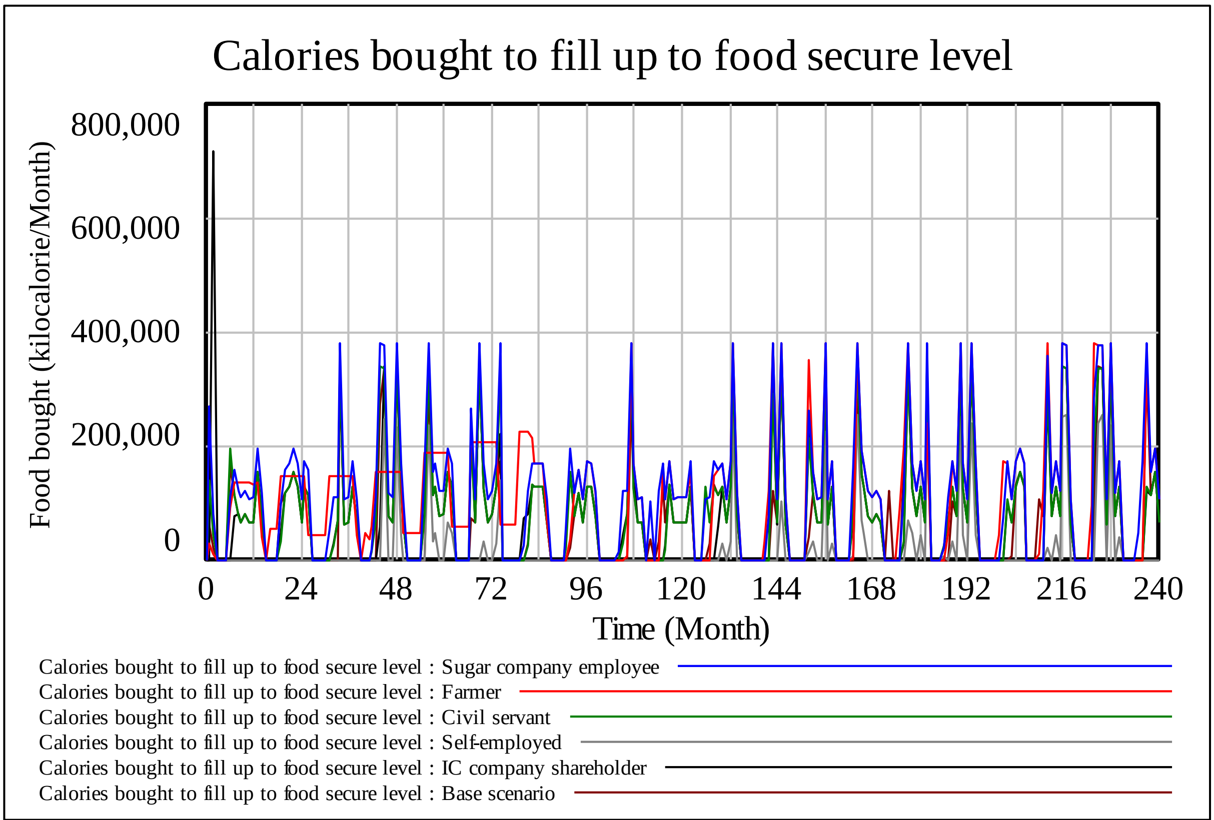

Figure 4-11: Types of households compared - Calories bought to fill up

other type of household not following the general trend, as that household has got plenty of food whenever others do not have.

From Figure 4-11 it is evident that households involved with IC companies by either being a shareholder or employed at one are the types of households that have to buy the most *Calories to fill up*. Fortunately, these types of households are also the types earning the highest salaries as shown in Figure 4-10, therefore they are still very food secure, but reliant on others to produce food. Figure 4-11 also indicates that the farming household was unable to buy enough food during the first 80 months, because of a lack of funds as illustrated in Figure 4-10.

4.5 Influence of Education and Occupation on food security

Preparing for this scenario, a few sub-scenarios was first run in order to be able to group some of the settings for the scenarios. Some of the sub-scenarios that were run can be seen in **Appendix E** in Figure A-0-30 to Figure A-0-39. The legend for *Education* and *Occupation* can also be found in Figure A-0-2 in **Appendix A**.

For this scenario, it was decided to split the household types into two groups. A good and a bad group. (This was based on the results of the sub-scenarios that was run and also only on the financial stand (Money available variable).) For each group that will be explained now, four different combinations of *Occupation* and *Education* will be compared. Another important note to take is that these two variables are the only two changed from that of the *Base scenario*.

The first group displayed in Table 4-5 is the bad group. This group consists of a farmer with no formal education, a farmer who completed college, a sugar company employee with no formal education and an artisan with some secondary school education.

Table 4-5: Variable values - Bad group (Occupation & Education)

Variable	Value				Unit
Scenario	**Farmer**	**Farmer**	**Sugar company employee**	**Artisan**	
Occupation	Farmer	Farmer	Sugar company employee	Artisan	
Education	No formal education	Completed college	No formal education	Some secondary school	

Salary	413.30	0	5447	2100	Emalangeni/Month
Household size	5.33	5.33	5.33	5.33	Person

Figure 4-13 illustrates that having no form of education, but working at a Sugar company is better than being a farmer who completed college. In addition it shows that there is only an E1080 difference between a farmer who has no formal education and one who completed college after twenty years. Being an Artisan who did some secondary school is better financially than being a farmer with a college degree/diploma.

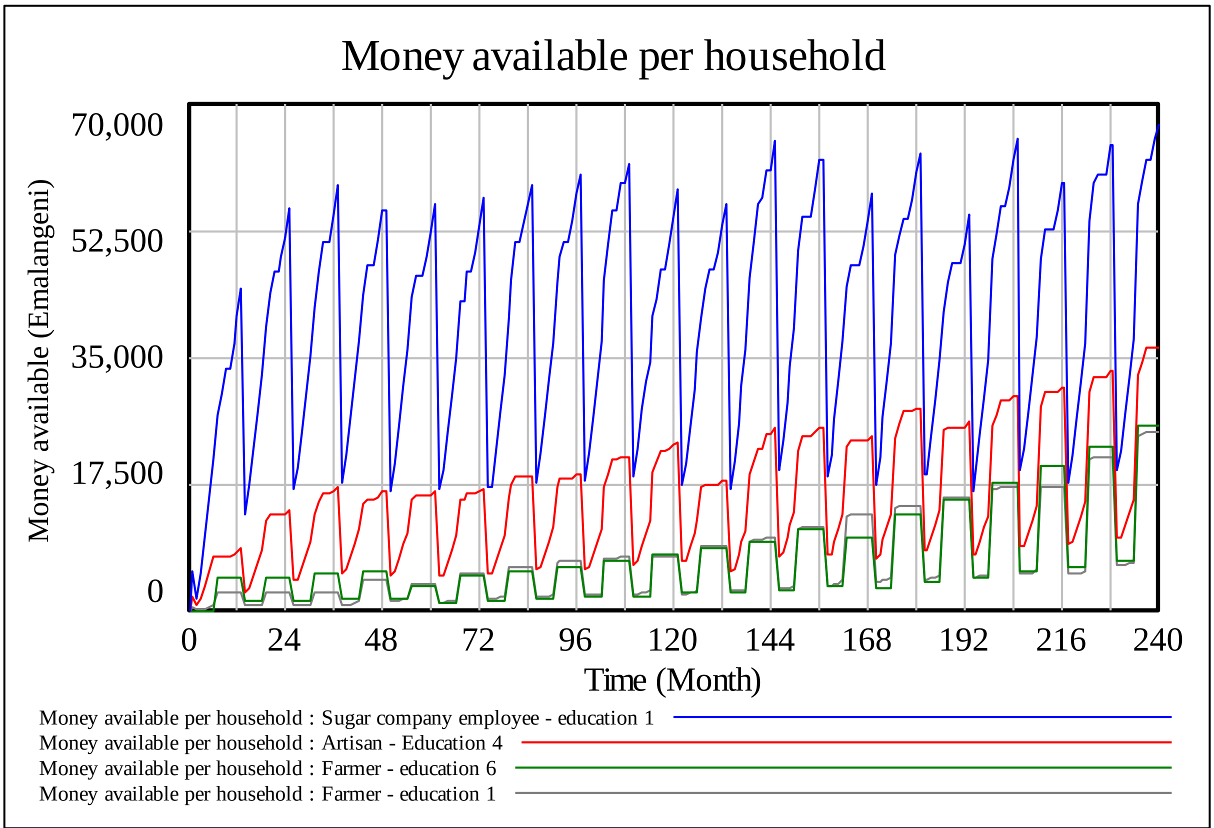

Figure 4-13: Bad group - Money available

The *Calories available* shown in Figure 4-14 illustrates an interesting site. It shows that a farmer with a college degree/diploma will be worse off for the first 13 months. Thereafter, only a household with a farmer with no formal education as head will be without food once, at month 45. All four types of households after that stays food secure.

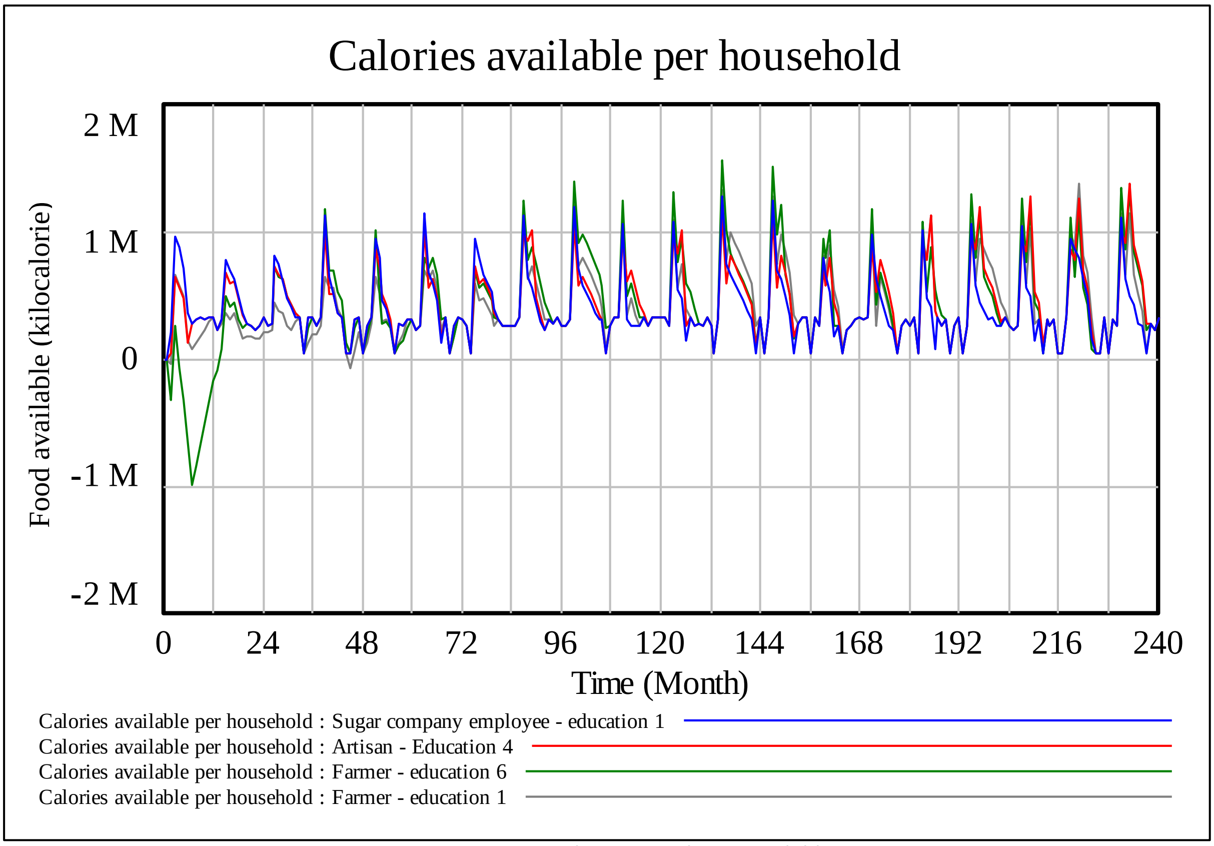

Figure 4-14: Bad group - Calories available

Next Table 4-6 represents the values for the variables of four "*good types"* of households. These include people as head of the house with the following education and occupation combinations; a retired person who completed secondary school, a sugar company employee who completed secondary school, a civil servant who completed secondary school and someone who is self-employed and completed postgraduate. Their salaries are much higher than that of the average person in Tshaneni as displayed in Table 4-6.

Table 4-6: Variable values - Good group (Occupation & Education)

Variable	Value				Unit
Scenario	**Retired**	**Sugar company employee**	**Civil servant**	**Self-employed**	
Occupation	Retired	Sugar company employee	Civil servant	Self-employed	
Education	Completed secondary school	Completed secondary school	Completed secondary school	Completed postgraduate	
Salary	7723	12930	4437	19010	Emalangeni/Month

Household size	5.33	5.33	5.33	5.33	Person

Figure 4-15 shows clear evidence that all four the households in this scenario will be very rich when compared to their counterparts in the community. They will have E271 200, E179 700, E109 900 and E62 090 respectively available in their accounts after twenty years. Compared to the maximum of the Bad group which was E67 300 and then E36 270 and downwards. Of the four households compared in this scenario, shown in Figure 4-15, the one with a self-employed head who completed a postgraduate will fare the best and have E271 200 available after twenty years. Second best will be a sugar company employee who completed secondary school.

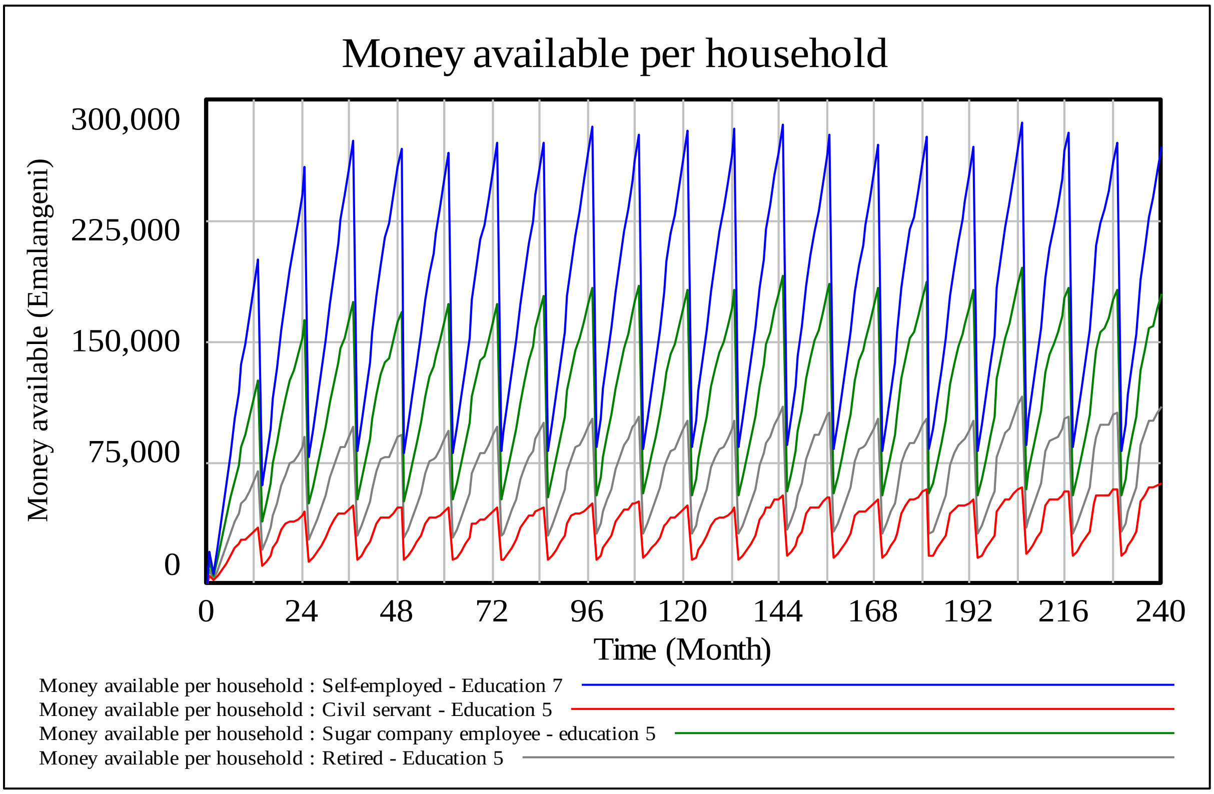

Figure 4-15: Good group - Money available

As expected, Figure 4-16 shows that none of these households was food insecure during the twenty year simulation period. Having this much capital definitely ensures their food security.

Some results found when doing the sub-scenario simulations (which is shown in **Appendix E**) was that being more educated does lead to being more food secure. This proved to be true for both the simulations run on a farmer as well as a sugar company employee. Through these sub-scenarios, another proven result indicated that the best occupation to pursue when someone in that area has finished secondary school is to become a sugar company employee.

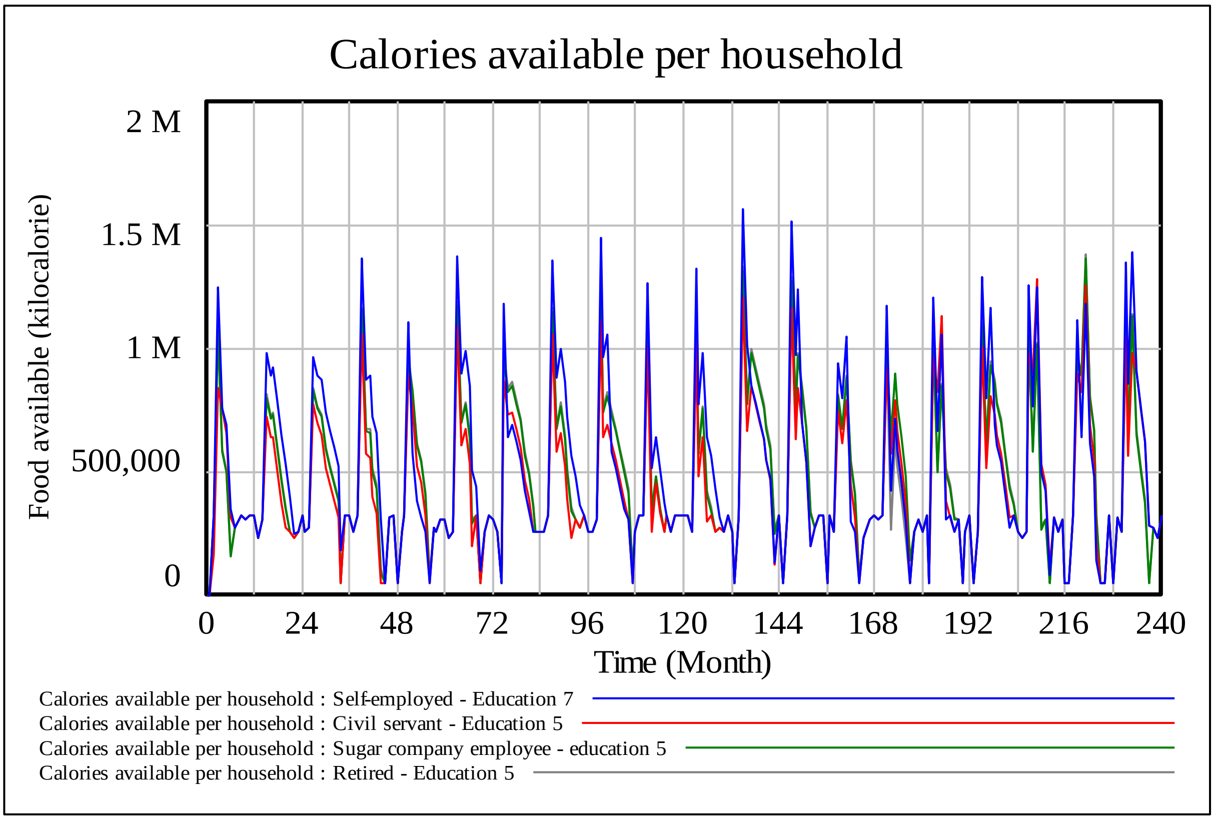

Figure 4-16: Good group - Calories available

The last finding from the sub-scenarios that was run was the top and bottom four combinations in terms of *Occupation* and *Education*, based on *Money available*. The top combinations can be seen ranked from best to worst in Table 4-7 below. The bottom or worst combinations is shown in Table 4-8. (Please note that being unemployed is excluded from this ranking as it will automatically mean zero income.) Being a farmer who completed his/her postgraduate is the ultimate combination for the Tshaneni area. In second place, the combination of postgraduate

Table 4-7: Top Occupation & Education combinations

Rank	Occupation	Education	Money available after twenty years (Emalangeni)
1	Farmer	Completed post graduate	865 700
2	Other than that mentioned in the questionnaire.	Completed postgraduate	708 300
3	Sugar company employee	Completed postgraduate	459 000
4	Sugar company employee	Completed college	291 400

and occupation that is not in the legend, shown in Figure A-0-2, is found. The third and fourth best involves people who are sugar company employees who either have a college degree/diploma or a post graduate.

Table 4-8 shows the worst performing combinations with regards to *Occupation* and *Education*. It illustrates that being a student (*Education* level does not matter) is the worst *Occupation* to have. The second worst combination is that of an Artisan who has done some primary school as someone like that will only have E22 810 available after twenty years. Third, you find a farmer who has done some primary school and fourth a retired person who has done some secondary school.

Table 4-8: Bottom - Occupation & Education combinations

Rank	Occupation	Education	Money available after twenty years (Emalangeni)
1	Student (All types but this is just an example)	Completed secondary school	367.70
2	Artisan	Some primary school	22 810
3	Farmer	Some primary school	23 730
4	Retired	Some secondary school	25 280

4.6 Conclusion Modelling results

This chapter quantified the five scenarios' input parameters and discussed the model findings of key output variables. The key output variables consisted of *Money available, Calories available* and *Calories bought to fill up*. These variables were compared for all the different scenarios as well as sub-scenarios that was run. It was found that the average household in the Tshaneni area, with the head of the house being an employed person, is food secure and will have accumulated E31800 at the end of twenty years. The second scenario showed that a household who is an IC company shareholder will be better off than the average household as they would have accumulated more money within the twenty years and were always able to buy calories to consume. The results of the next scenario showed that whenever a prolonged drought came that the average household in Tshaneni will not be food secure, as they will not harvest enough crops to consume and also not have enough *Money available* to buy the calories needed. The fourth scenario compared different types of typical households in the area. The results indicated that a farming household with 6 members in the household will not be food secure under normal circumstances. The scenario also indicated that in the long run, it will be better to be a sugar company employee (serving on the board) than being an IC company shareholder, which was an interesting find. Being part of a typical household while the head of the household is a civil servant proves to be a very food secure situation. The last scenario of the chapter indicated that education does have an influence on food security. In addition it indicated which careers should be pursued by a young person in the area who just completed secondary school. The top occupations, as well as the bottom ones, are shown in Table 4-7 and Table 4-8. Finally, the scenario pointed out that being involved in IC companies in any way does prove to ensure that a household is food secure.

The next chapter which is also the last chapter of the study discuss the results and findings of the modelling outcomes through the scenarios. Recommendations are made to stakeholders and policymakers based on the findings. The limitations of the study as well as future improvements are also discussed.

Chapter 5 : Study conclusions & recommendations

Chapter 4 discussed the results obtained from the different scenarios that were run. Three main output variables were discussed namely: *Money available; Calories available* and *Calories bought to fill up*. Each scenario tried to answer the question regarding what the impact of industrial crops is on food security by changing different main input variable values. In total five scenarios were run and the last two each included different sub-scenarios that were compared to one another.

This chapter provides a conclusion to the research as a whole and aims to provide answers or solutions to the research objectives stated in section **1.5**. Next recommendations are made based on the findings with the help of the scenarios. The recommendations are aimed at stakeholders as well as policymakers in order to have an impact on the real system and improve the quality of life and food security stance of the people from Swaziland. The limitations that the model, process or model boundaries had is also discussed and sequentially recommendations for future research in this area or on the model.

First, the important findings from each scenario will be highlighted and discussed.

5.1 Important model findings

Important model findings were made in the previous chapter which are summarized now before recommendations are made within the next section. There are five different modelling scenarios as discussed in section **3.4.2**. The detailed results for each of these scenarios can be found in **Chapter 4** and now the interpretation of the results will be explained.

5.1.1 Base scenario findings

The results (section **4.1**) from this scenario shows that the average household with an employed head of the house, who receive off-farm income, will be food secure. The results are as expected. As the years went by, the amount of *Money available* accumulated and the number of *Calories available* followed a periodical trend, as expected, because of harvesting season. Whenever the household did not have enough *Calories available* they would buy some with their available money.

5.1.2 IC company shareholder findings

This scenario was the first scenario to ask the question of the impact of ICs on food security for Swaziland, Tshaneni. The results (section **4.2**) however proved that when a household became part of an FA and therefore a shareholder of an IC company, then they would be better off financially than the Base scenario household. More money will be accumulated by a household who is an IC company shareholder over the twenty years than one who is not. Since finance is not the only measure of food security the number of *Calories available* should also be taken into consideration. It is clear that a household from this scenario will have to buy more food, but since they have the funds available it is no problem as they prove to always be food secure.

Something worth noticing as well is the fact that since more funds are available to buy fertilizer and irrigation is accessible to them, the yields they obtain are a lot higher and they are almost able to produce just as much food on their smaller piece of available cropping land than the average household in the area. This means that they need to buy more food than the base household, but less than originally expected.

There is also more seasonality that can be picked up as the amount of dividends received every year differs, compared to the rather stable income from the base household. Then again, even at the worst time (seasonality), the household proved to stay food secure.

5.1.3 Climate variability scenario findings

This scenario's results (section **4.3**) showed that the average household in Swaziland is not equipped or prepared to handle a prolonged drought. Financially they will not be able to survive and it will be impossible to produce enough food for themselves unless they are able to acquire some form of irrigation and maybe fertilizer. Whenever there is irrigation then a household or person is way more resilient to a system shock like a prolonged drought. This is shown through the previous scenario and is evident when looking at the yields obtained by a household that is an IC company shareholder, which can only be obtained through the means of irrigation or an extremely good rain year. The advantage of irrigation above a good rain year is that water can be applied at any time and therefore at the exact needed time by the crop, which is more important than just getting enough water in a season. This proves that households that are IC company shareholders are more resilient to climatic shocks like prolonged droughts since they have access to irrigation.

5.1.4 Types of households compared findings

Different typical households from the area were compared in this scenario. From the six different types of households that were compared the household with a head who is a sugar company employee proved to be the most successful financially after twenty years through the results shown in section **4.4**. This was an interesting find and the reason behind it might be because of the seasonality when an IC company shareholder compared to the stability of being employed and having a constant salary. On the other hand, a farming household with an extra member proved to be the worst off financially.

This scenario proved that either being an employee of an IC company or being an IC company shareholder is a better position to be in, than most other household types in the area, when considering food security. It also showed that whenever a household increase in size, then it will become more difficult providing for them, as expected.

5.1.5 Influence of Education and Occupation on food security

From the results that were obtained in section **4.5**, a few points can be highlighted. The first point is that the higher level of education a person has, the more food secure they will be. This is illustrated by all the results from this scenario. Secondly, this scenario shows that a person's occupation is also very important when measuring food security. All occupations related to ICs are worth pursuing, while occupations related to high levels of education is also a guarantee for food security. Occupations that predict less food security includes farming, being a student, being an artisan or being retired. The worst cases include these occupations with very low education levels, whilst all the best cases include very high levels of education and IC company involvement or farming.

5.1.6 Overall model findings

The overall model findings indicate that the involvement in industrial crops does lead to better food security. The reasons are increased household incomes, the availability of irrigation and the access to inputs like fertilizers and pesticides. Something that the model does not show directly but is also worth mentioning is the fact that a lot of development comes with the expansion of industrial crops. It is also evident that even though food is more expensive when bought than grown, people involved in IC companies, are still very food secure since they have the needed funds to buy enough food.

Therefore the **Impacts of industrial crops on food security in Swaziland** proves to be very positive in terms of development and food security.

5.2 Recommendation to stakeholders

The last research step of the research strategy used to complete the objectives, as described in section **1.5**, is to *give interpretations of the model to stakeholders which will include personnel from the sugar industry, SWADE, government and any other interested parties*. Therefore this section interprets the results and provides recommendations to the all of the involved stakeholders and policymakers. (This will be presented to them in Swaziland at the beginning of December 2017.)

Through the results of this simulation model and scenarios that were tested, it is evident that industrial crop expansion is very positive and leads to households and communities being more food secure. Therefore IC expansion is encouraged as it empowers the people and leads to community development as well. Public health increases as IC crops expand, because of the people being more food secure and the fact that RSSC has a hospital that is funded by them for their employees (Ntiwane, 2016). Future investments in IC expansion projects (specifically sugarcane in this case) are therefore encouraged.

5.3 Model limitations

The model definitely has some limitations in terms of system behaviour and other variables that were not included during the construction of the model that could have helped increase accuracy. Some of the limitations were caused by a time constraint and others by modelling difficulty.

The first limitation of the model is that of livestock kept. The amount of livestock kept was balanced by more or less keeping births equal to deaths plus those sold, but in reality, there are many other factors that play a role in the amount of livestock that can be kept, especially in tribal areas like these where livestock grazes on communal land. It was too complex to include all the different factors and some of the practices done in terms of livestock farming in those areas are also unknown.

Sugar yields are assumed to be constant. It is assumed that no matter what the weather situation is, a constant sugarcane yield will be generated. The reasoning behind it is that irrigation is available for the plantations and therefore assumed that even in dry years enough water can be given to the sugarcane to ensure a constant yield. This is not the case in the real system as it is known that drought also plays a role even on irrigated crops. So does bad irrigation practices, but it is rather assumed that the people know what they are doing and therefore getting constant yields.

A limitation of the model also is the consistency of data. The data that was gathered by the FICESSA team in Swaziland was at some parts not as complete as hoped. It is believed that this is because of the people not actually measuring their yields and amount of food bought or that people would have measured it through different indicators which caused inconsistency. Additionally, the year 2016 in which the survey was done in the area was an extremely dry year where some households reported that they planted crops, but then the same households did not report harvesting any crops.

The amount of calories households consume that come from livestock is nowhere documented clearly and it is known that in many places the livestock is only kept as wealth and may be consumed at events like funerals. This caused the assumption that very low numbers of calories consumed by a household does indeed come from the meat of livestock. The exact amount consumed is thus not known and since the model is very sensitive to this, it might change some of the outcomes if the real system amounts differ a lot from what was assumed.

Financial management by the people in terms of the amount of money saved or wasted is not known and assumed as investments made in the *Economic stand* sub-model. If this specific area can be better understood, then this will lead to a more accurate model.

The only climatic scenario or shock that is taken into account is the lack of rain/water. All other climatic factors, which does also play a major role in terms of yields, is not taken into account. These factors include climate change, soil composition and timing of rain. If they could be included then the model would have been even more accurate.

The model does not take micronutrients into consideration and is just concerned with the number of calories that is available to a household, not where they come from and what other nutrients accompany them. This was decided since the field of malnourishment is a field of study on its own that is an unfamiliar field to the modeller.

System dynamics is a very dynamic way of modelling and the model built does not necessarily use all the dynamic power of system dynamics. This is said because there are certain parts that could have been modelled more dynamically but was not because of time constraints.

5.4 Suggested future research

Some future research has been identified during the study. This includes research in terms of model improvements or other sectors that can also be modelled that was identified, but not done because of time constraints.

All the limitations mentioned in the previous section can also be considered as future research for this research since removing them will result in a more accurate model which will be even more useful to support arguments and scenarios. Other suggested future research would be to include data from other areas of Swaziland as well. There are other areas that are also involved in IC growing (for example sugar plantations close to Big bend), which also includes other types of ICs (cotton & jatropha). If all these areas and all the different types of ICs could be included in the same model, then a very comprehensive understanding will be gained which will be very useful.

Building the model at a regional level rather than at a household level will provide answers to other questions like whether communities involved in IC expansions are more food secure than those not involved. The model will then be in a more common format that allows it to be compared to other areas from all over the world will be easier.

Future work that is also recommended is to include a more in-depth model regarding food security and include health and food varieties as well as vitamin intake and stunting.

5.5 Research reflections

Some insightful lessons were learned while conducting this study and therefore this section aims to communicate the most notable lessons regarding modelling problems like this as well as noteworthy findings that could help future researchers doing similar research. Similar research in the sense of modelling dynamic problems or doing research in sub-Saharan Africa countries.

5.5.1 Using system dynamics modelling to model a problem

System dynamics modelling is a very efficient way to model dynamic problems that consist of qualitative as well as quantitative data. It is simple enough to use as a basic approach yet complex enough to model any type of problem in as much detail as needed. It is worth mentioning that as the complexity increase the time it takes to model increases exponentially.

Most other modelling methods categorise variables into independent bundles which interact with one another, but not necessarily on the whole system. This is not the case with system dynamics as it allows all variables to interact dynamically as they would in the real system, therefore making it a more realistic model. If the problem at hand is however simple and not aggregated enough then system dynamics will not be the recommended choice of modelling method, as it can be modelled a lot easier through the use of other methods like Microsoft Excel.

Understanding the software and the basics of system dynamics and VensimPro is not too difficult, but as the complexity of the model increases so does the required understanding of the software. Therefore modelling complex systems can be laborious, but the end result can be extremely accurate.

It is known that through SDM, qualitative variables can be incorporated, but quantifying the relationships can be very difficult. A problem arises when the model is very sensitive to these values and therefore qualitative variables should be entered with care into the models and their influences should be clearly understood before they are just entered and relationships about them are assumed. With that said, in general, SDM is rather robust and can withstand a bit of inaccurate data.

A problem that arose that in order to build an accurate and complete SDM, knowledge about all the relevant fields is required. Through building this specific model, knowledge about farming practices, the economy, climate change, food sciences, business practices, cultural beliefs and operations, modelling and engineering and social sciences had to be gained in order to build the model. It is very powerful being able to work across so many fields with one model, but it is also easy to build a model without understanding the real relationships which make the model built obsolete.

SDM is a powerful “tool” to have and it is a very efficient way of communicating across fields and even to people not familiar with certain fields. Managers and stakeholders can use SDM to experiment with model outputs without changing the model structure or requiring the assistance of the modeller. Choosing the right scenarios to run is also a very important phase of SDM because only when asking the right questions, the right answers can be obtained through SDM.

5.5.2 Noteworthy findings

Through the study, some noteworthy findings were made that might help future researchers. In most cases when doing a postgraduate study it is difficult to obtain data and it is the main obstacle for in-time completion of many people’s theses. Through this study it was realised that whenever the data needed comes from other sub-Sahara Africa countries, then that obstacle becomes even more evident. Therefore some advice on whenever data has to be collected from one of these countries would be to go there and do fieldwork. In most cases sending emails did not help at all (this is obviously not always the case), the best way was to go to the offices of whomever data was needed and ask for an appointment. It should also be realised that the data needed might not have been captured, so it is good to be flexible when doing research in this field. If it is at all possible to use data that have been collected by other teams in the field, then it is advised.

Another noteworthy finding was that whenever a project that includes this much social science has to be done by an engineer, then it is advised to consult an expert in the social science field, as certain assumptions or ways of saying/writing things might offend people without it being the purpose. This does however not only count for social sciences but any field that is unfamiliar to the researcher.

Lastly whenever feedback about research has to be given to stakeholders then it is important to do it in such a way so that everybody will understand the outcomes and results. It is therefore important to remember that everybody is not familiar with engineering terms and practices and will not understand all of them. This was realised when presentations were made to extremely qualified people, but not necessarily engineers in London. Therefore it is important to know which terms or concepts have to be explained before presenting about them and not to assume that the audience knows.

5.6 Concluding remarks

Swaziland is a country full of potential and IC expansion (specifically sugarcane) has the potential to help lots of poverty stricken rural communities, to be food secure. Large scale IC plantations have brought a lot of development in the areas where research was done and the perception of people with regards to IC expansion is very positive, therefore future investments in this sector is encouraged. It empowers the people and creates lots of jobs as well as other spin-off businesses.

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Appendix

Appendix A – Stock and flow diagrams

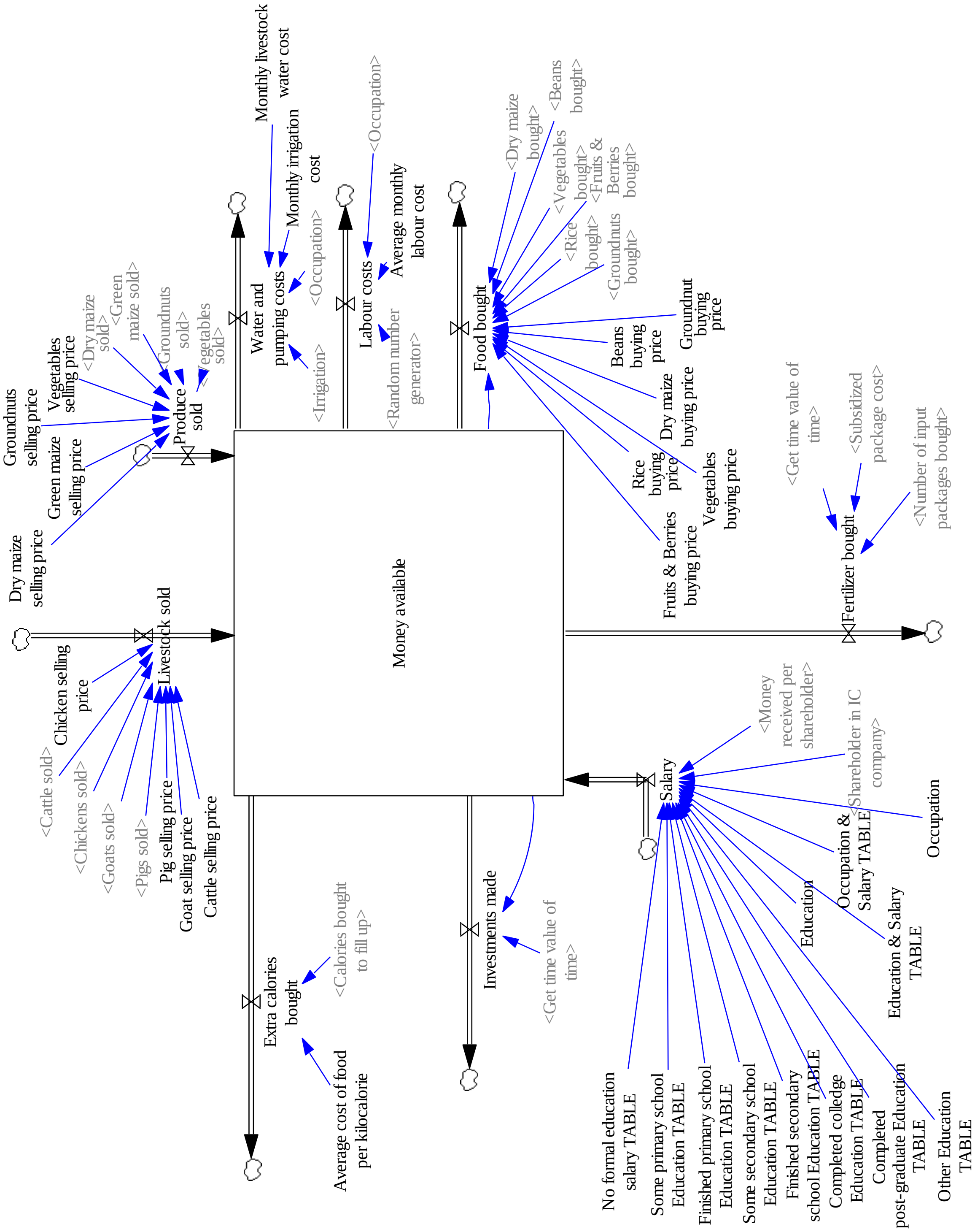


Figure A-0-1: Stock and flow diagram - Economic stand

Education legend

1 - No formal schooling
2 - Some primary school
3 - Completed primary school
4 - Some secondary school
5 - Completed secondary school
6 - Completed colledge
7 - Completed post graduate
8 - Other

Occupation legend

1 - Farmer
2 - Sugar company employee
3 - Other agricultural labourer
4 - Artisan
5 - Civil servant
6 - Self employed/own business
7 - Student
8 - Unemployed
9 - Retired
10 - Other

Figure A-0-2: Education & Occupation legends for stack and flow diagrams

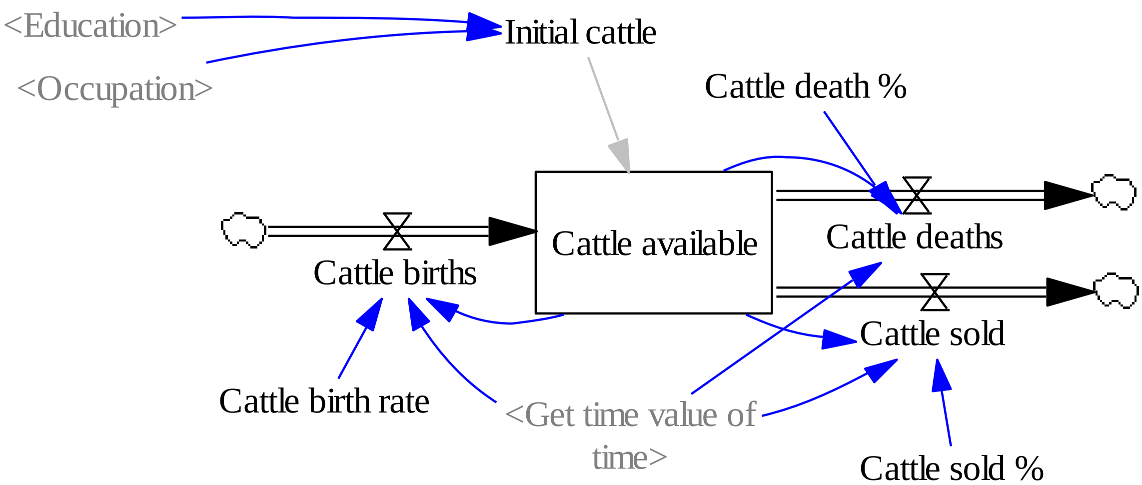


Figure A-0-3: Cattle stock and flow

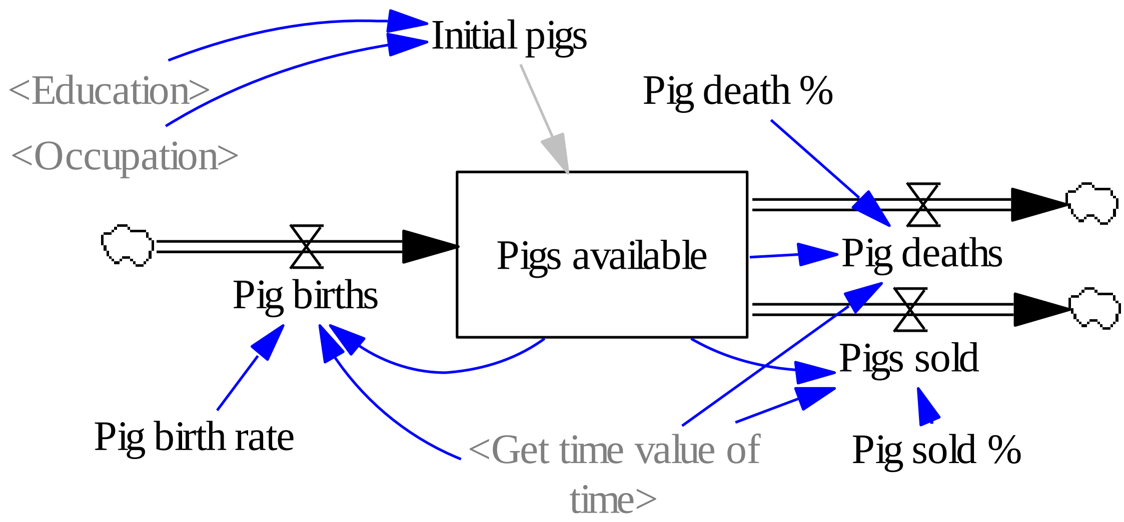


Figure A-0-5: Pigs stock and flow diagram

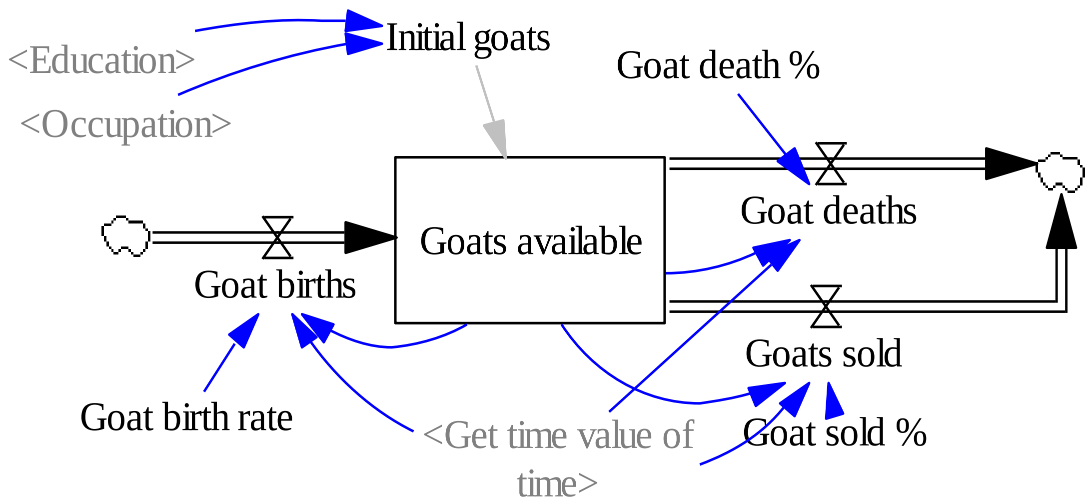


Figure A-0-6: Goats stock and flow diagram

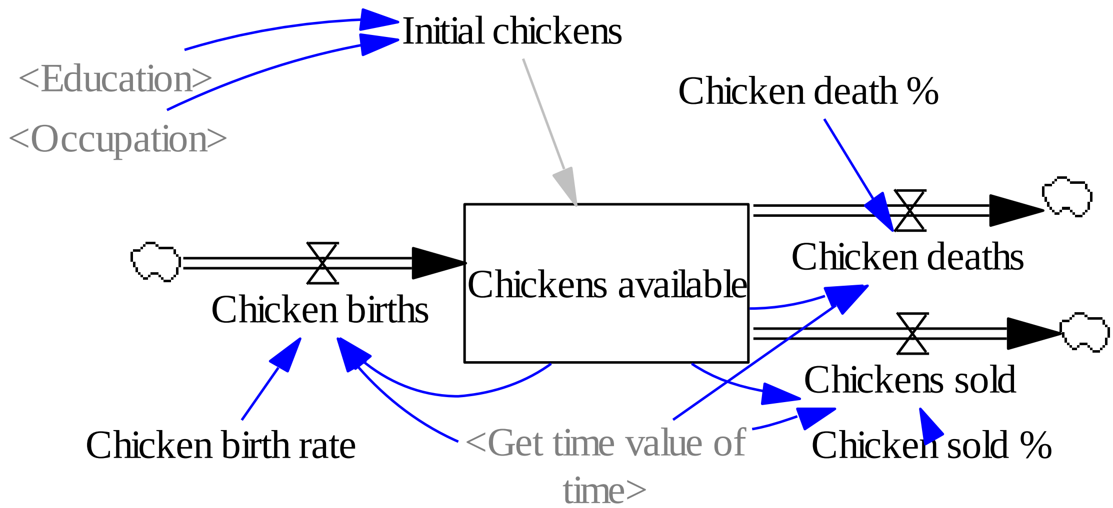


Figure A-0-4: Chickens stock and flow diagram

Appendix

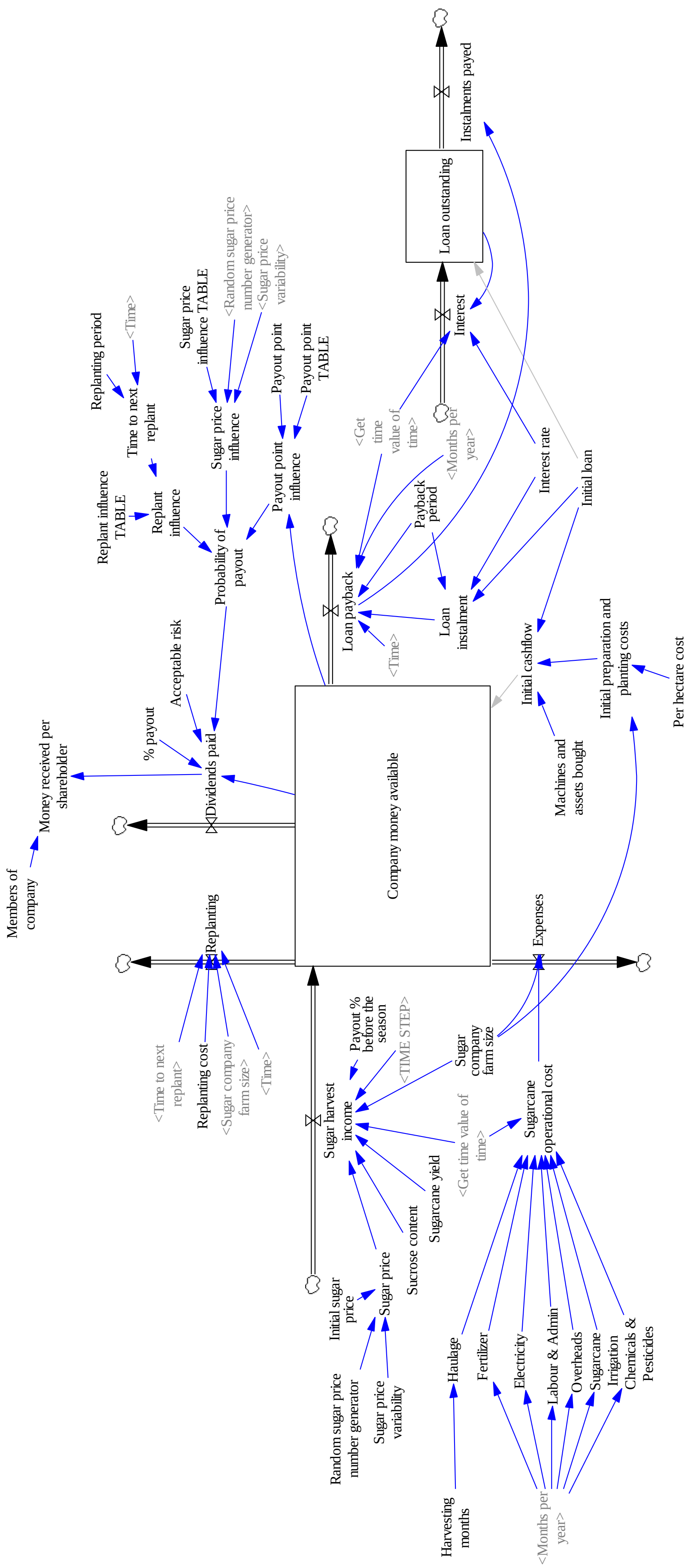


Figure A-0-7: Industrial crops stock and flow diagram

Appendix

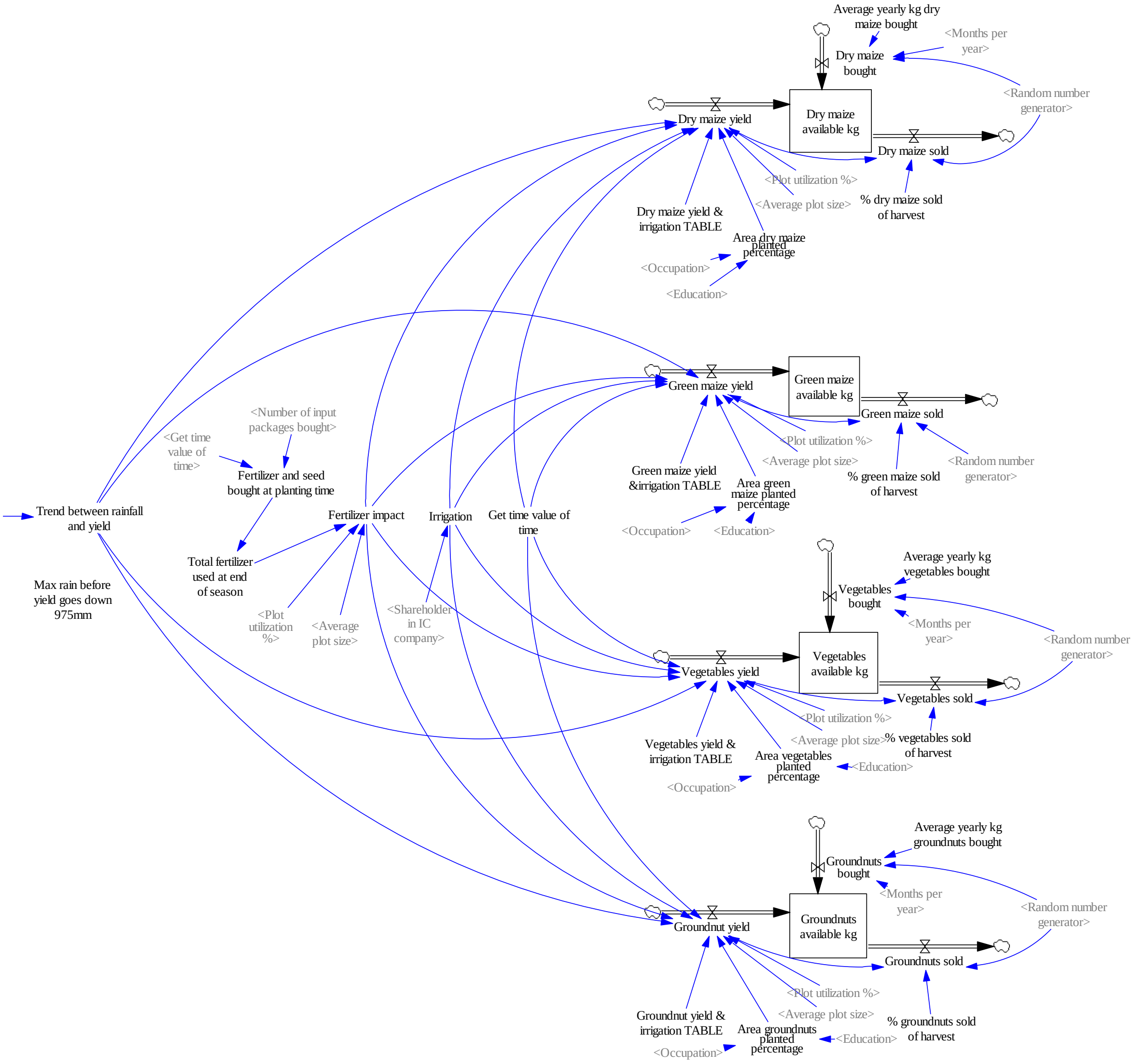


Figure A-0-8: Crops grown main stock and flow diagram

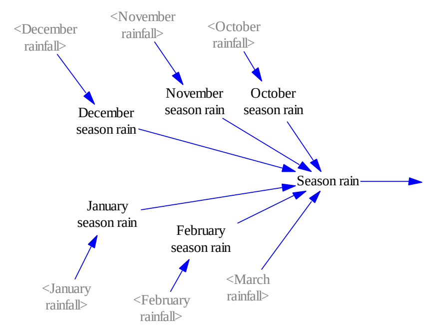


Figure A-0-9: Rainfall for crops grown stock and flow diagram

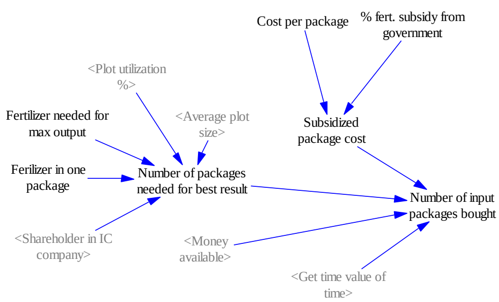


Figure A-0-10: Fertilizer subsidy for crops grown stock and flow diagram

Appendix

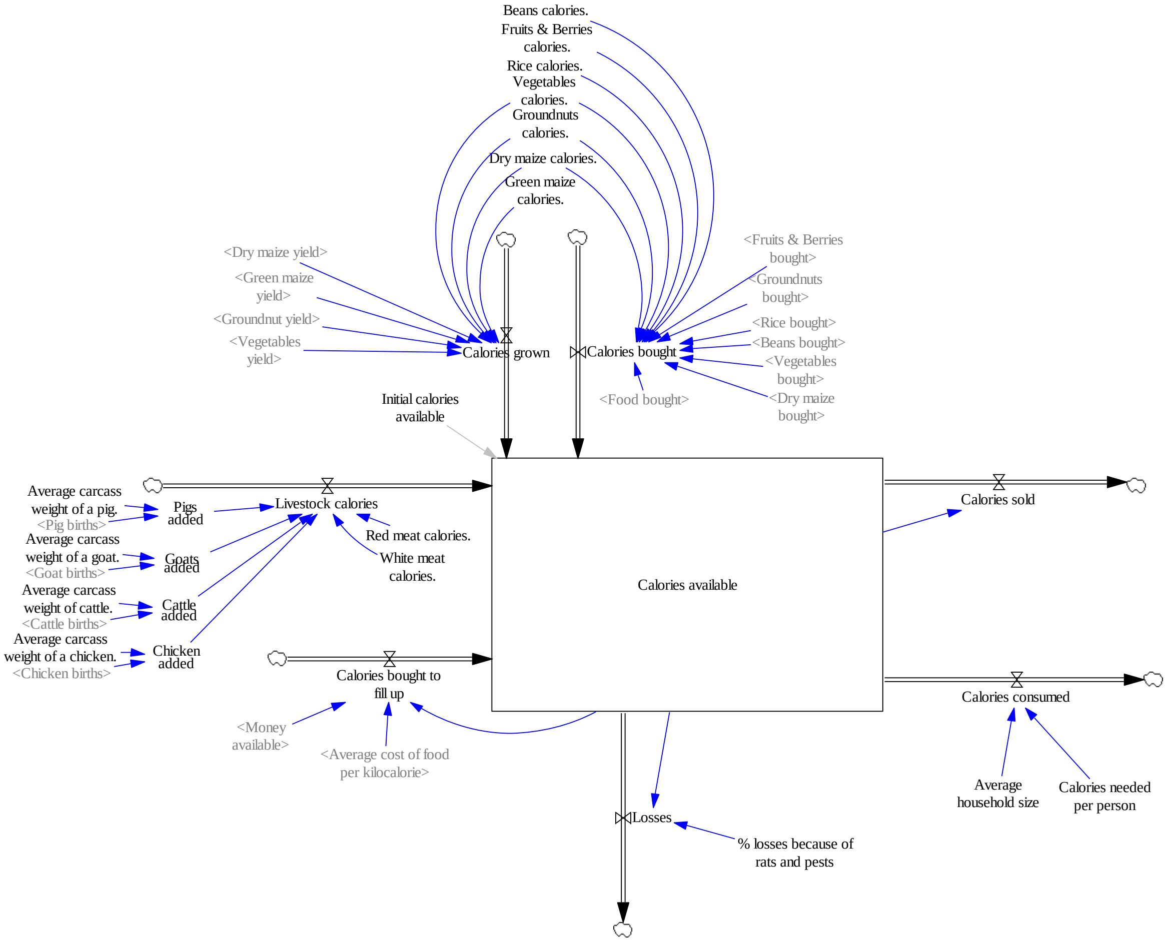
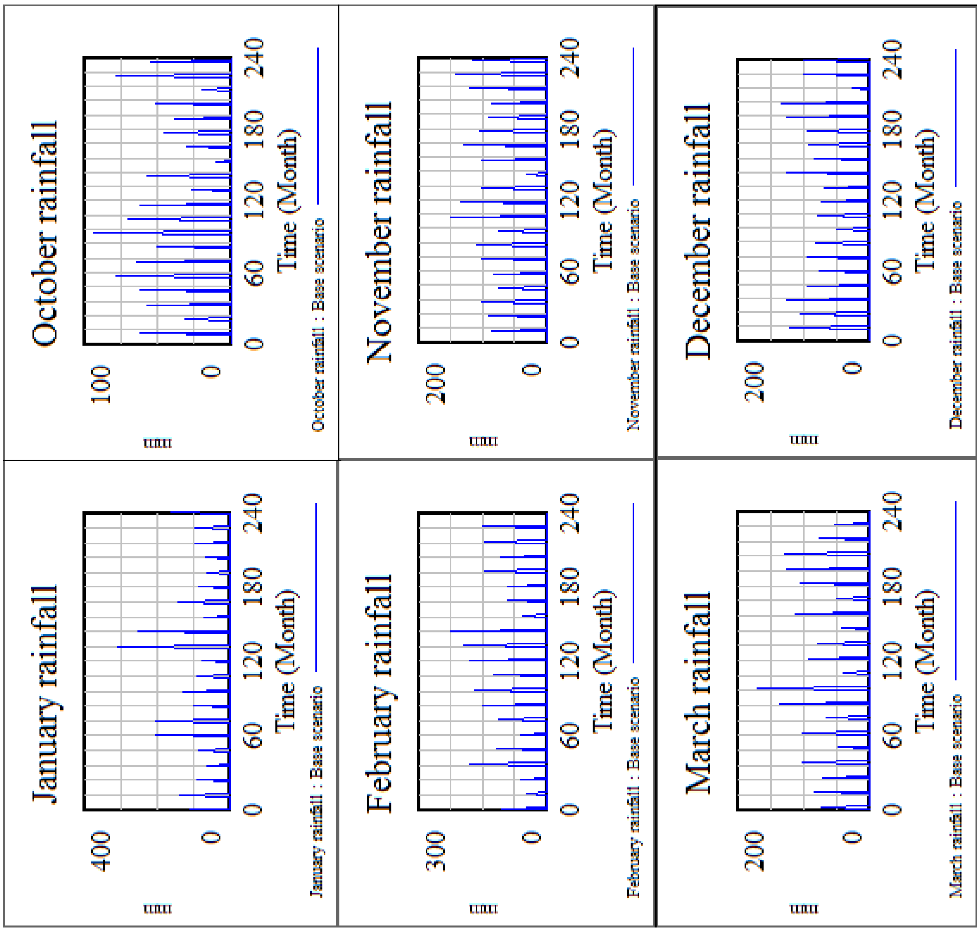


Figure A-0-11: Food consumption stock and flow diagram

Appendix



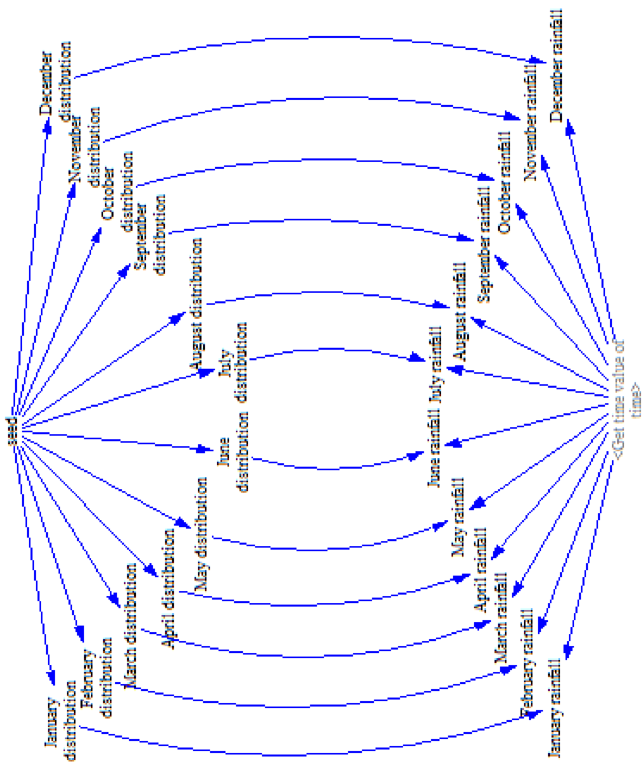


Figure A-0-12: Rainfall stock and flow diagram

Appendix B – Variable values and sources tables

Exogenous variables

Table A-0-1: Exogenous variable values and sources

Variable	Value	Unit	Source
Economic stand			
Average cost of food per kilocalorie	0.0196	Emalangeni(E)/kilocalorie E1 = R1	(Numbeo, 2017)
Cattle selling price	3457.19	E/Cattle	FICESSA survey
Goat selling price	665.85	E/Goat	
Pig selling price	413.46	E/Pig	
Chicken selling price	33.46	E/Chicken	
Dry maize selling price	2.06	E/kg	
Green maize selling price	11.29		
Groundnuts selling price	5.29		
Vegetable selling price	8.36		
Monthly livestock water price	69.98	E/month	
Monthly irrigation cost	238.76		
Average monthly labour cost	90.97		
Fruits & Berries buying price	4.69	E/kg	
Rice buying price	8.91		
Vegetable buying price	4.63		
Dry maize buying price	7.64		
Beans buying price	17.13		
Groundnut buying price	15.38		
Livestock kept			
Cattle birth rate	0.7	Births/cattle	FICESSA survey
Goat birth rate	1	Births/goats	

Pig birth rate	0.7	Births/pigs	
Chicken birth rate	4	Births/chicken	
Cattle sold %	33	% of total	
Goat sold %	30		
Pig sold %	50		
Chicken sold %	77		
Cattle death %	18.6		(Obert, et al., 2013)
Goat death %	18.6		
Pig death %	18.6		
Chicken death %	18.6		
Industrial crops grown			
Haulage	814.50	E/hectare(ha)	(SWADE, 2012)
Fertilizer	3421.05	E/(year x ha)	
Electricity	3421.05		
Labour & admin	1791.98		
Overheads	977.44		
Sugarcane irrigation	488.72		
Chemicals & pesticides	488.72		
Sugar price variability	0.2	Dimentionless	Through testing and validation with real system.
Initial sugar price	2979	E/ton	(SWADE, 2012)
Sucrose content	0.1425	Of total weight	
Sugarcane yield	100	Ton/ha	
Sugar company farm size	178.8	Ha	
Pay out % before the season	5	% of total	
Replanting cost	6000	E/ha	
Machines and assets bought	1 500 000	E	

Per hectare cost (preparation and planting)	5000	E/ha	
Initial loan	10 000 000	E	
Interest rate	10	%	
Payback period	10	Years	
Pay out point	15 000 000	E	Through testing and validation with real system.
Replanting period	10	Years	(Baucum, et al., 2015)
Acceptable risk	20	%	Through testing and validation with real system.
% pay out (dividends)	40	%	
Members of company	106	People	(SWADE, 2012)
Crops grown			
Fertilizer needed for max output	400	Kg/ha	(African centre for biodiversity, 2016)
Fertilizer in one package	300	Kg	
Cost per package	4000	E	
% fertilizer subsidy from government	50	% of total	
Average yearly kg dry maize bought	603.76	Kg/year	FICESSA survey
Average yearly kg vegetables bought	277.79		
Average yearly kg groundnuts bought	78.58		
% dry maize sold of harvest	60	% of total	
% green maize sold of harvest	60		
% vegetables sold of harvest	70		

% groundnuts sold of harvest			
Max rain before yield goes down	975	mm	
Trend between rainfall and yield	Parabolic function	$(-2.66 \times 10^{-6}) \times (\text{season rain})^2 + (0.005187 \times \text{season rain}) - 1.01386$	(Oseni & Masarirambi, 2011)
Fertilizer impact	Limit	$(11000 \times (1 - e^{(-0.015 \times ((\text{total fertilizer used at end of season}/(\text{average plot size} \times \text{plot utilization \%})) + 47.87))}))/5677$	(Crista, et al., 2014)
Food consumption			
Red meat calories	1895	Kilocalorie/kg	(United States Department of Agriculture , 2017)
White meat calories	1800		
Beans calories	1550		
Fruits & Berries calories	570		
Rice calories	1300		
Vegetables calories	600		(Anon., 2017)
Groundnuts calories	5670		
Dry maize calories	3650		(United States Department of Agriculture , 2017)
Green maize calories	860		
Average household size	5.33	Person	FICESSA survey
Calories needed per person	2085.5	Kilocalories/person/day	Moderate active average from (Kakwani & Son, 2015)
% losses because of rats and pests	16.5	%/year	(Mdangi, et al., 2013)
Avg carcass weight of a pig	40	kg	(Engelbrecht, 2017)
Avg carcass weight of a goat	20		
Avg carcass weight of cattle	180		

Avg carcass weight of a chicken			
Rainfall			
January Min	36.92	mm	(THE WORLD BANK GROUP, 1901 - 2015)
Max	311.04		
Mean	131.06		
Standard deviation	53.15		
February Min	21.45		
Max	283.83		
Mean	115.38		
Standard deviation	50.78		
March Min	17.08		
Max	194.66		
Mean	84.49		
Standard deviation	31.87		
April Min	4.66		
Max	140.81		
Mean	42.44		
Standard deviation	23.6		
May Min	0.36		
Max	77.42		
Mean	18.4		
Standard deviation	14.48		
June Min	0.06		
Max	57.1		
Mean	9.96		
Standard deviation	10.97		
July Min	0.26		
Max	71.99		
Mean	11.43		
Standard deviation	13.65		
August Min	0.35		
Max	63.52		
Mean	10.33		
Standard deviation	13.62		

September Min	1.19		
Max	157.92		
Mean	27.94		
Standard deviation	27.6		
October Min	8.76		
Max	197.7		
Mean	56.74		
Standard deviation	32.38		
November Min	27.65		
Max	199.31		
Mean	89.83		
Standard deviation	35.42		
December Min	19.78		
Max	212.71		
Mean	106.35		
Standard deviation	37.98		

Endogenous variables

Table A-0-2: Endogenous variables

Endogenous variables			
Economic stand			
Extra calories bought	Investments made	Salary	Fertilizer bought
Food bought	Labour cost	Water and pumping costs	Produce sold
Livestock sold	Money available		
Livestock kept			
Cattle births	Cattle deaths	Cattle sold	Pig births
Pig deaths	Pigs sold	Goat births	Goat deaths
Goats sold	Chicken births	Chicken deaths	Chickens sold
Cattle available	Pigs available	Goats available	Chicken available
Industrial crops grown			
Sugar price	Sugar harvest income	Sugarcane operational cost	Expenses
Initial preparation and planting costs	Initial cash flow	Loan instalment	Loan payback
Interest	Instalments payed	Pay out point influence	Sugar price influence
Time to next replant	Replant influence	Probability of pay out	Dividends paid

Money received per shareholder	Replanting	Company money available	Loan outstanding
Crops grown			
Number of packages needed for best result	Subsidized package cost	Number of input packages bought	December season rain
November season rain	October season rain	January season rain	February season rain
Season rain	Trend between rainfall and yield	Fertilizer and seed bought at planting time	Total fertilizer used at end of season
Fertilizer impact	Irrigation	Dry maize yield	Area dry maize planted percentage
Dry maize bought	Dry maize sold	Green maize yield	Area green maize planted percentage
Green maize sold	Vegetables bought	Vegetables yield	Area vegetables planted percentage
Vegetables sold	Groundnut yield	Area groundnuts planted percentage	Groundnuts bought
Groundnuts sold	Dry maize available kg	Green maize available kg	Vegetables available kg
Groundnuts available kg			
Food consumption			
Pigs added	Goats added	Cattle added	Chicken added
Livestock calories	Calories bought to fill up	Losses	Calories consumed
Calories sold	Calories grown	Calories bought	Calories available
Rainfall			
January rainfall	February rainfall	March rainfall	April rainfall
May rainfall	June rainfall	July rainfall	August rainfall
September rainfall	October rainfall	November rainfall	December rainfall

Excluded variables

Table A-0-3: Excluded variables

Excluded variables			
Milk from livestock as calories	Eggs from chicken as calories	Soil properties	Temperature
Climate change	Inflation	Labour as limiting factor	Other ICs
Deaths to households	Other areas outside of Tshaneni	Corruption	Theft
Possibility to acquire land through purchase	Vitamin and other nutritional needs		

Appendix C – Stock and flow formulas extended

From **Equation 3-1:**

***Salary* (r_{sal}) =** IF THEN ELSE(Shareholder in IC company=1, IF THEN ELSE(Education=0, "Occupation & Salary TABLE"(0), IF THEN ELSE(Occupation =0, "Education & Salary TABLE"(0), IF THEN ELSE (Education=1, No formal education salary TABLE(Occupation), IF THEN ELSE(Education=2, Some primary school Education TABLE(Occupation), IF THEN ELSE(Education=3, Finished primary school Education TABLE(Occupation), IF THEN ELSE(Education=4, Some secondary school Education TABLE(Occupation), IF THEN ELSE(Education=5, Finished secondary school Education TABLE(Occupation), IF THEN ELSE(Education=6, Completed college Education TABLE(Occupation), IF THEN ELSE(Education=7, "Completed post-graduate Education TABLE"(Occupation), IF THEN ELSE(Education=8, Other Education TABLE(Occupation), 0))))))))))+Money received per shareholder, IF THEN ELSE(Education=0, "Occupation & Salary TABLE"(0), IF THEN ELSE(Occupation=0, "Education & Salary TABLE"(0), IF THEN ELSE(Education=1, No formal education salary TABLE(Occupation), IF THEN ELSE(Education=2, Some primary school Education TABLE(Occupation), IF THEN ELSE(Education=3, Finished primary school Education TABLE(Occupation), IF THEN ELSE(Education=4, Some secondary school Education TABLE(Occupation), IF THEN ELSE(Education=5, Finished secondary school Education TABLE(Occupation), IF THEN ELSE(Education=6,Completed colledge Education TABLE(Occupation), IF THEN ELSE(Education=7, "Completed post-graduate Education TABLE"(Occupation), IF THEN ELSE(Education=8, Other Education TABLE(Occupation), 0)))))))))))

***Livestock sold* (r_{lss}) =** (Cattle selling price*Cattle sold)+(Chicken selling price*Chickens sold)+(Goat selling price*Goats sold)+(Pig selling price*Pigs sold)

***Produce sold* (r_{pds}) =** (Dry maize selling price*Dry maize sold)+(Green maize selling price*Green maize sold)+(Groundnuts selling price*Groundnuts sold)+(Vegetables selling price*Vegetables sold)

***Fertilizer bought* (r_{fzb}) =** IF THEN ELSE(Get time value of time=3, Number of input packages bought*Subsidized package cost, 0)

***Food bought* (r_{fdb}) =** IF THEN ELSE(Money available<100, 0, (Beans bought*Beans buying price)+(Dry maize bought*Dry maize buying price)+("Fruits & Berries bought"*"Fruits & Berries buying price")+(Groundnut buying price*Groundnuts bought)+(Rice bought*Rice buying price)+(Vegetables bought*Vegetables buying price))

Labour costs **(r_{lbc}) =** IF THEN ELSE(Occupation=7, 0, IF THEN ELSE(Random number generator<0.105, Average monthly labour cost, 0))

Water and pumping costs **(r_{wpc}) =** IF THEN ELSE(Occupation=7, 0, IF THEN ELSE(Irrigation=1, Monthly irrigation cost, IF THEN ELSE(Irrigation=2, Monthly irrigation cost/3*2, IF THEN ELSE(Irrigation=3, Monthly irrigation cost/3, 0))))+IF THEN ELSE(Occupation=7, 0, Monthly livestock water cost)

Extra calories bought **(r_{ecb}) =** Calories bought to fill up*Average cost of food per kilocalorie

Investments made **(r_{inm}) =** IF THEN ELSE(Get time value of time=7, Money available*0.7, 0)

From **Equation 3-2:**

Births **(r_{bir}) =** IF THEN ELSE(Get time value of time=3, Livestock available*Livestock birth rate, 0)

Deaths **(r_{deh}) =** IF THEN ELSE(Get time value of time=10, INTEGER(Livestock available*"Livestock death %"), 0)

Livestock sold **(r_{lss}) =** IF THEN ELSE(Get time value of time=12, INTEGER("Livestock sold %"*Livestock available), 0)

From **Equation 3-3:**

Sugar harvest income **(r_{shi}) =** IF THEN ELSE(Get time value of time=5, (Sugarcane yield*Sugar company farm size*Sucrose content*Sugar price)*(1-"Payout % before the season"), IF THEN ELSE(Get time value of time=7, (Sugarcane yield*Sugar company farm size*Sucrose content*Sugar price)*"Payout % before the season", 0))/TIME STEP

Expenses **(r_{exs}) =** Sugar company farm size*Sugarcane operational cost

Sugarcane operational cost = IF THEN ELSE(Get time value of time>=10:OR:Get time value of time<=4, Haulage, 0)+"Chemicals & Pesticides"+Electricity+Fertilizer+"Labour & Admin"+Overheads+Sugarcane Irrigation

Replanting **(r_{rep}) =** IF THEN ELSE(Time>1, IF THEN ELSE(Time to next replant=0, Replanting cost*Sugar company farm size, 0), 0)

Loan payback **(r_{lpb}) =** IF THEN ELSE((Months per year*Payback period)>=Time, IF THEN ELSE(Get time value of time=5, Loan instalment, 0), 0)

Dividends paid **(r_{ddp}) =** IF THEN ELSE(Probability of payout>=(1-Acceptable risk), Company money available*"% payout", 0)

From **Equation 3-4:**

Interest **(r_{int}) =** IF THEN ELSE(Get time value of time=6, Loan outstanding*Interest rate, 0)

Instalments payed **(r_{isp}) =** Loan payback

From **Equation 3-5:**

Crops bought **(r_{cbt}) =** IF THEN ELSE(Random number generator<0.8139, Average yearly kg dry maize bought/Months per year, 0)

Or

= IF THEN ELSE(Random number generator<0.4574, Average yearly kg vegetables bought/Months per year, 0)

Or

= IF THEN ELSE(Random number generator<0.4185, Average yearly kg groundnuts bought/Months per year, 0)

Crop yield **(r_{cyd}) =** IF THEN ELSE(Get time value of time=8, "Crop yield & irrigation TABLE"(Irrigation)*Trend between rainfall and yield*Fertilizer impact, 0)*Average plot size*Area crop planted percentage*"Plot utilization %"

Crop sold **(r_{csd}) =** IF THEN ELSE(Random number generator<0.0188, "% crop sold of harvest"*crop yield, 0)

From **Equation 3-6:**

***Livestock calories* (r_{lsc}) =** Chicken added*"White meat calories." + Cattle added*"Red meat calories" + Pigs added*"White meat calories" + Goats added*"Red meat calories"

***Calories grown* (r_{csg}) =** "Dry maize calories."*Dry maize yield+"Green maize calories."*Green maize yield+Groundnut yield*"Groundnuts calories."+"Vegetables calories."*Vegetables yield

***Calories bought* (r_{csb}) =** IF THEN ELSE(Food bought=0, 0, Beans bought*"Beans calories."+Dry maize bought*"Dry maize calories."+"Fruits & Berries bought"*"Fruits & Berries calories."+ Groundnuts bought*"Groundnuts calories." + Rice bought*"Rice calories." + Vegetables bought*"Vegetables calories.")

***Calories bought to fill up* (r_{cbf}) =** IF THEN ELSE(Calories available<383525, IF THEN ELSE(Money available>((383525- Calories available)*Average cost of food per kilocalorie), 383525-Calories available, IF THEN ELSE(Money available<((383525- Calories available)*Average cost of food per kilocalorie), Money available/Average cost of food per kilocalorie, 0)), 0)

***Loses* (r_{los}) =** MAX(Calories available*"% losses because of rats and pests", 0)

***Calories sold* (r_{css}) =** IF THEN ELSE(Calories available>1e+006, 400000, 0)

***Calories consumed* (r_{ccd}) =** DELAY FIXED (Average household size*Calories needed per person, 1, 0)

Foot note: All the IF THEN ELSE used is to ensure that tasks are executed at the right time of year, since the model is run in months and there are many different variables that follow different trends.

Appendix D – Stock and flow lookup table graphs

Table A-0-4: Education & Occupation legend

Numerical value	Education	Occupation
1	No formal education	Farmer
2	Some primary school	Sugar company employee
3	Completed primary school	Other agricultural labourer
4	Some secondary school	Artisan
5	Completed secondary school	Civil servant
6	Completed college	Self-employed/own business
7	Completed post graduate	Student
8	Other	Unemployed
9		Retired
10		Other

Economic stand lookup graphs

Each economic stand lookup graph represent one coulomb of a matrix with occupation on the x-axis and education on the y-axis with salary as the link.

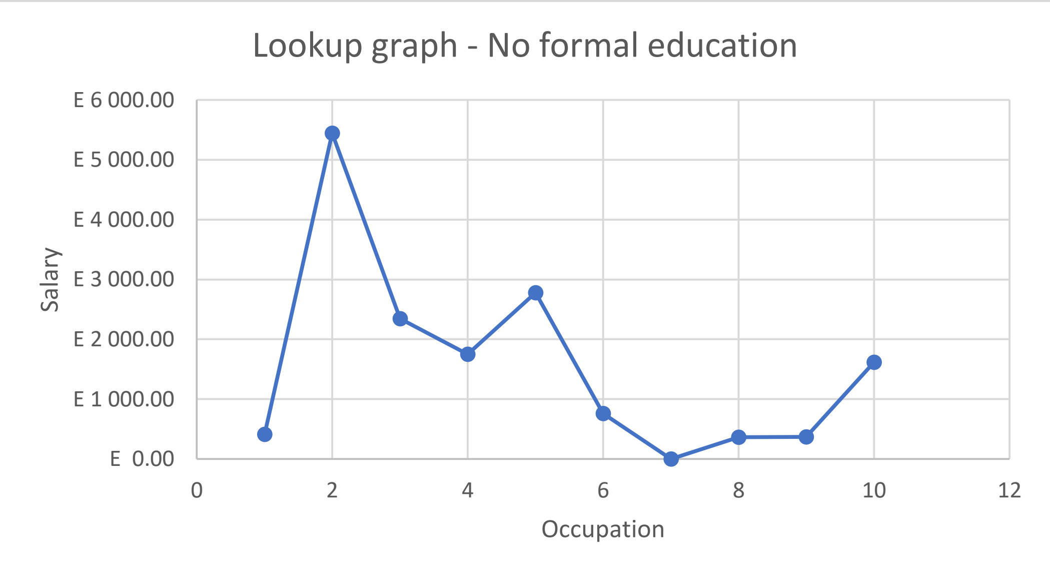


Figure A-0-13: Lookup graph - No formal education

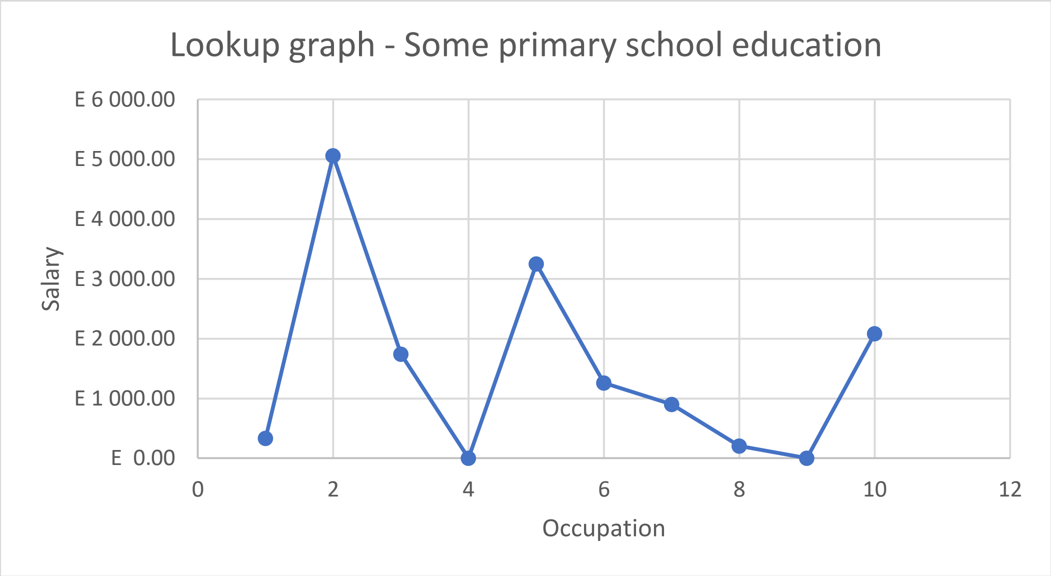


Figure A-0-14: Lookup graph - Some primary school

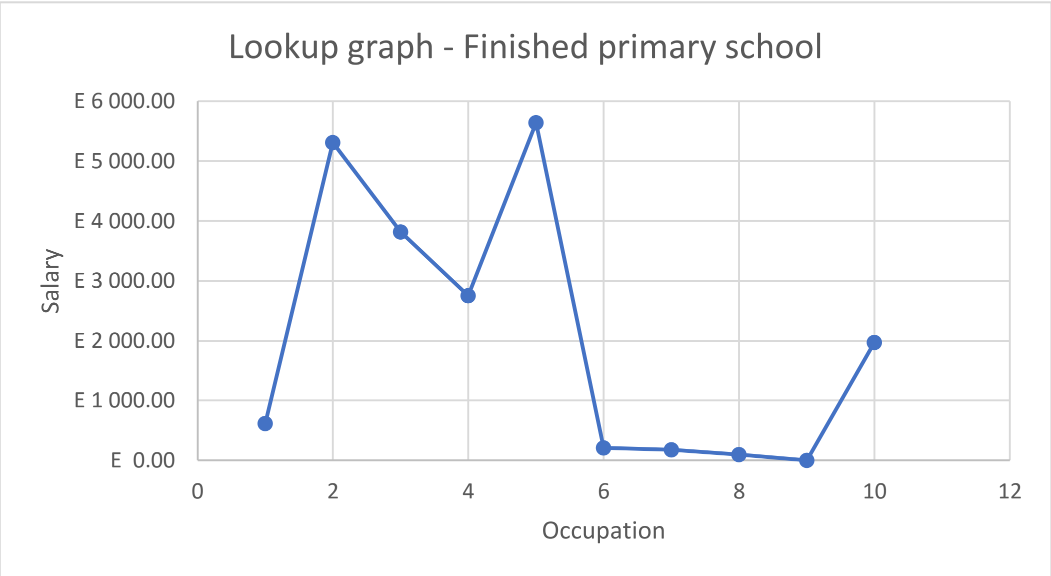


Figure A-0-15: Lookup graph - Finished primary school

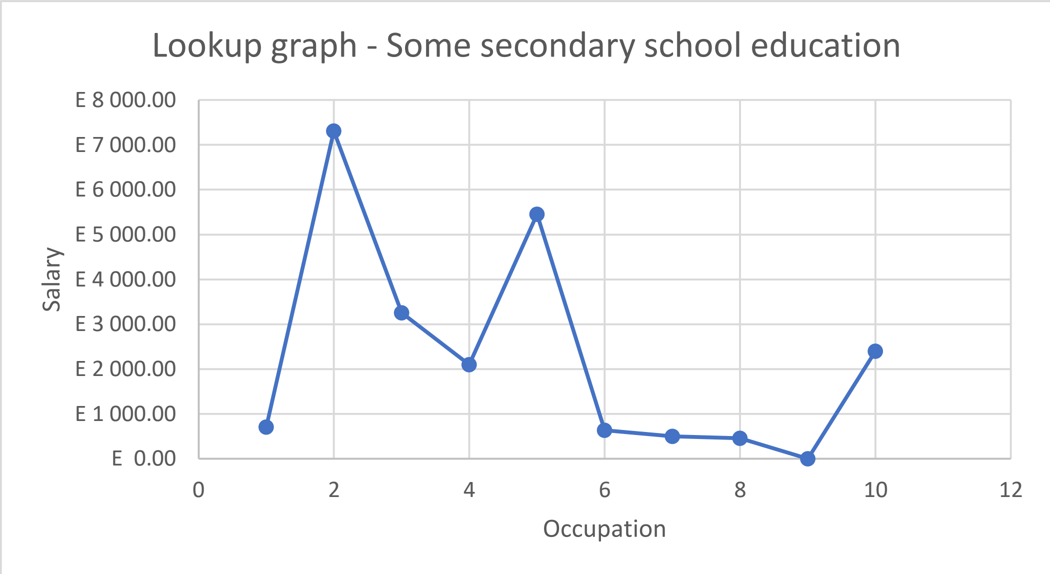


Figure A-0-16: Lookup graph - Some secondary school

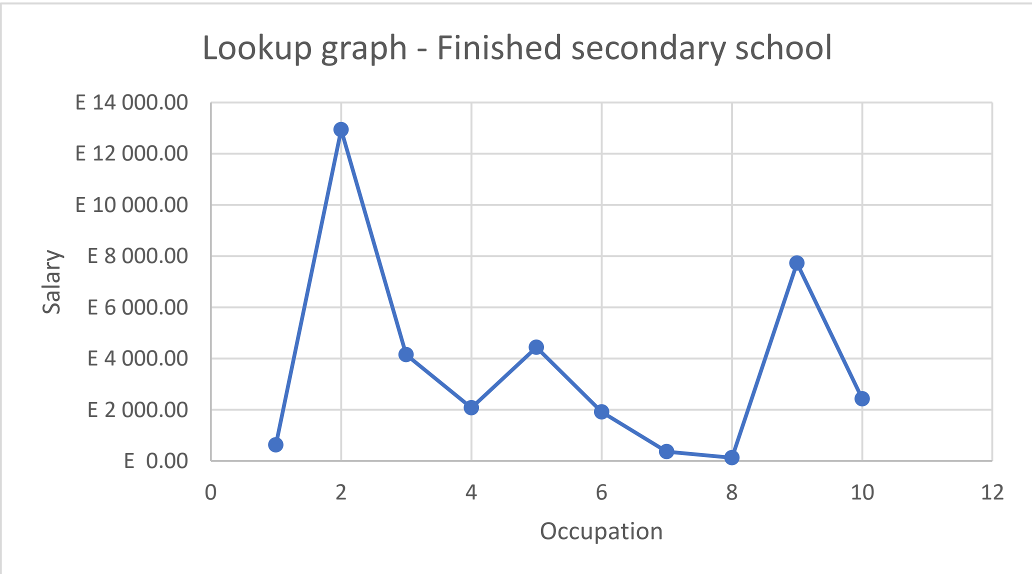


Figure A-0-17: Lookup graph - Finished secondary school

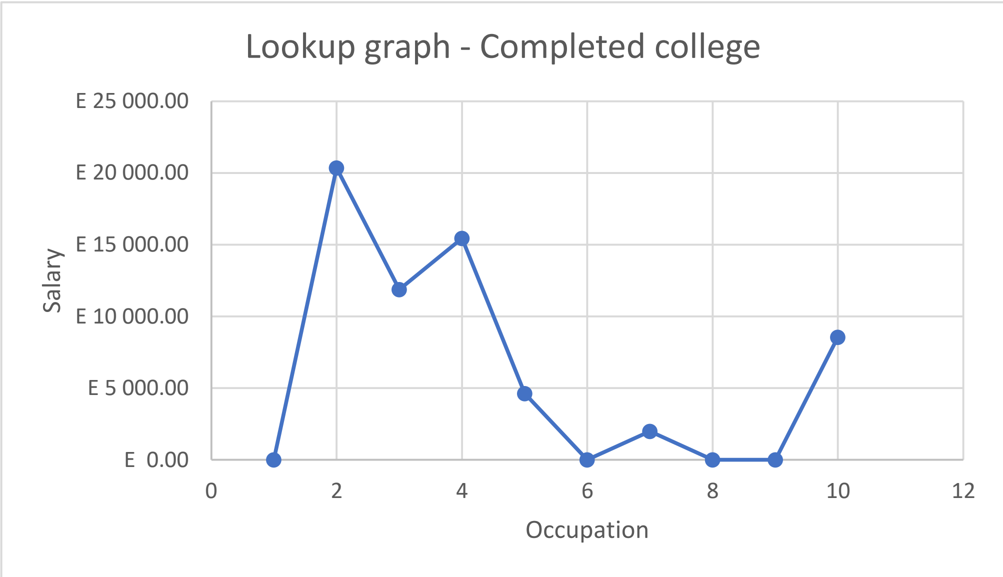


Figure A-0-18: Lookup graph - Completed college

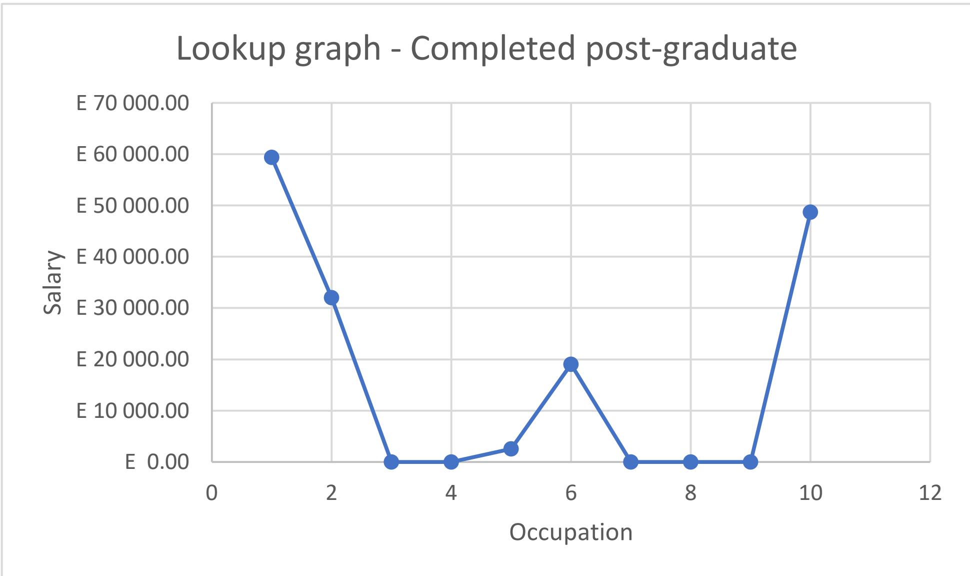


Figure A-0-19: Lookup graph - Completed post-graduate

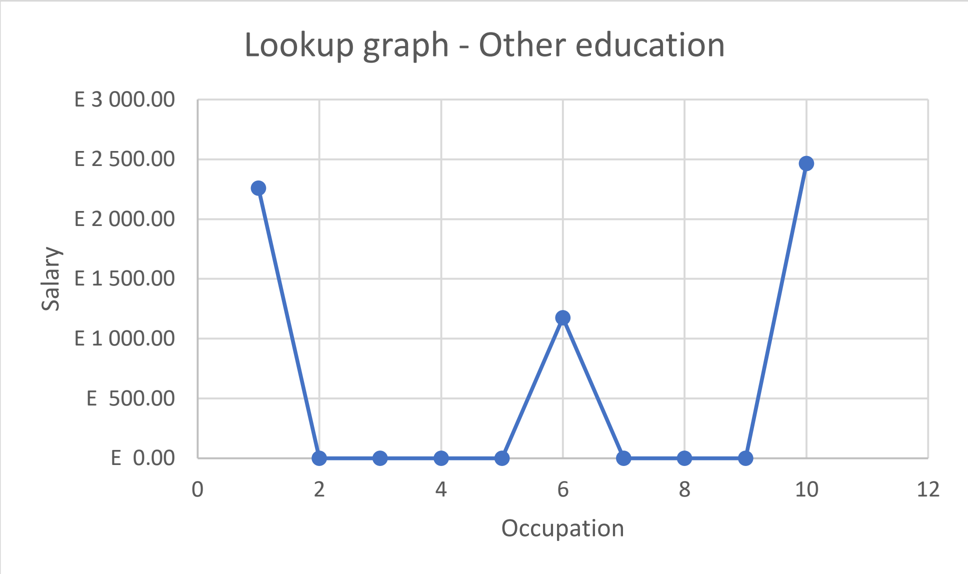


Figure A-0-20: Lookup graph - Other education

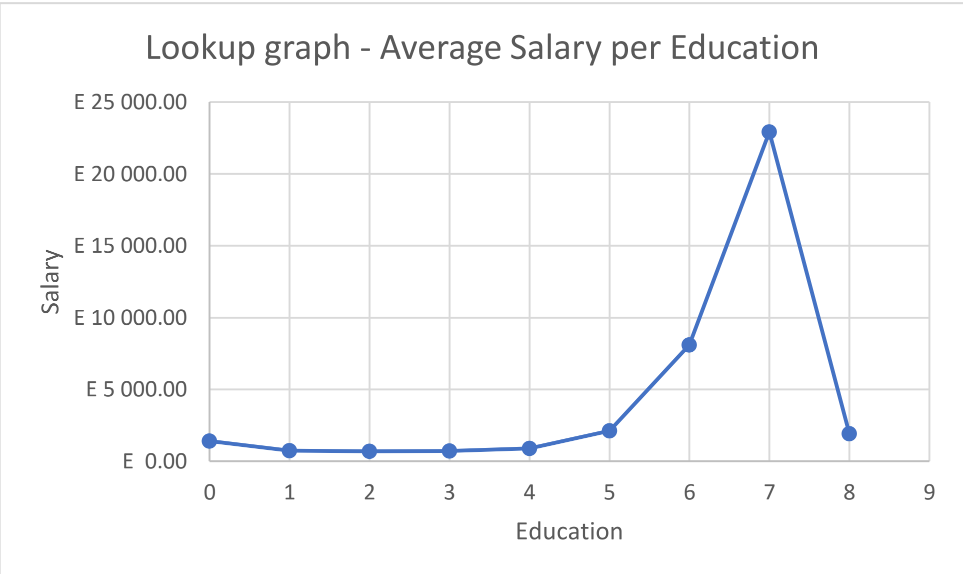


Figure A-0-21: Lookup graph - Average salary per education

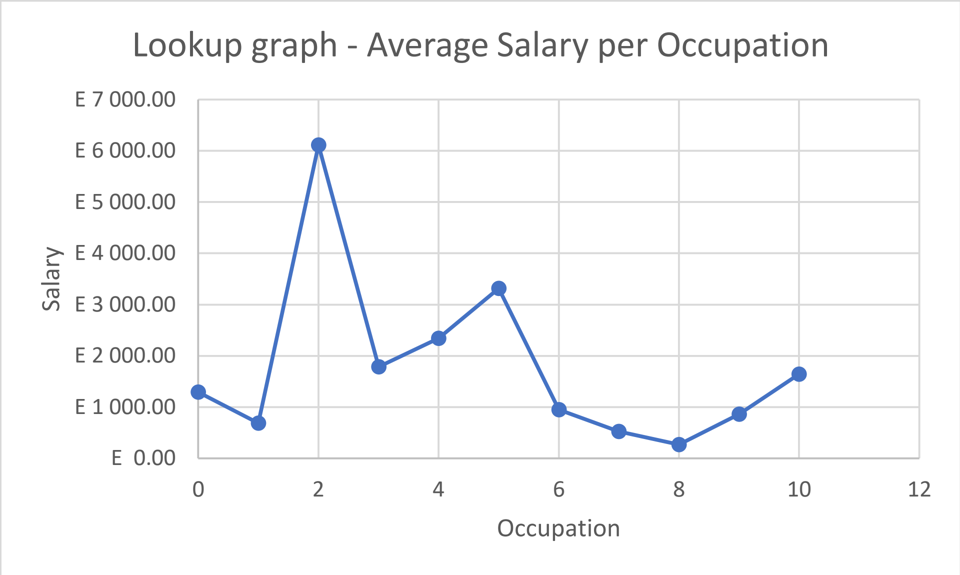


Figure A-0-22: Lookup graph - Average salary per occupation

Industrial crops grown lookup graphs

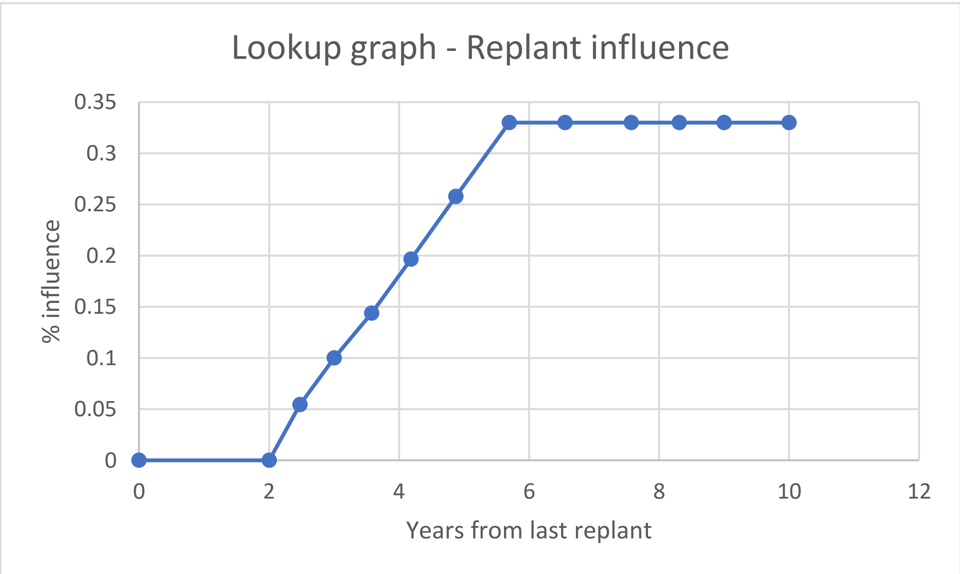


Figure A-0-23: Lookup graph - Replant influence

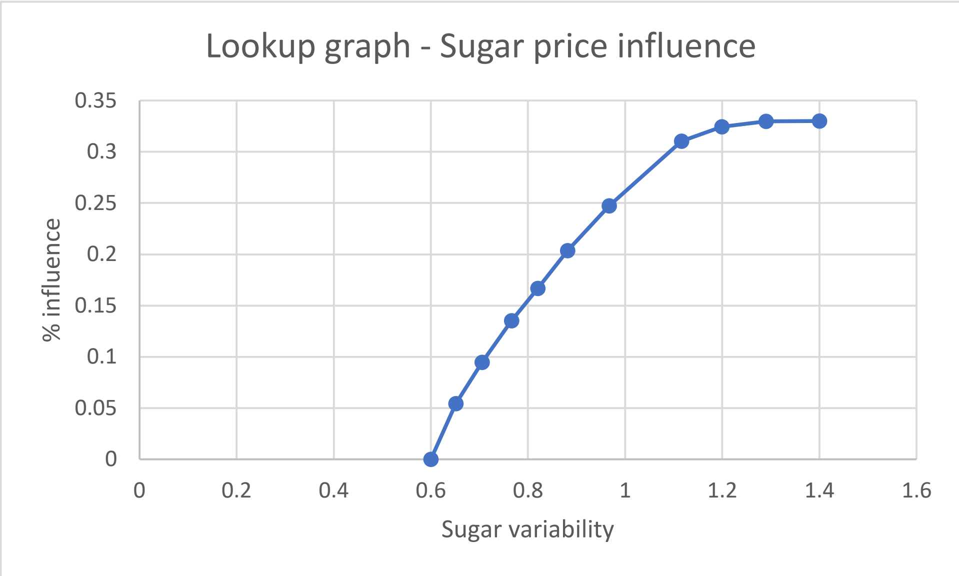


Figure A-0-24: Lookup graph - Sugar price influence

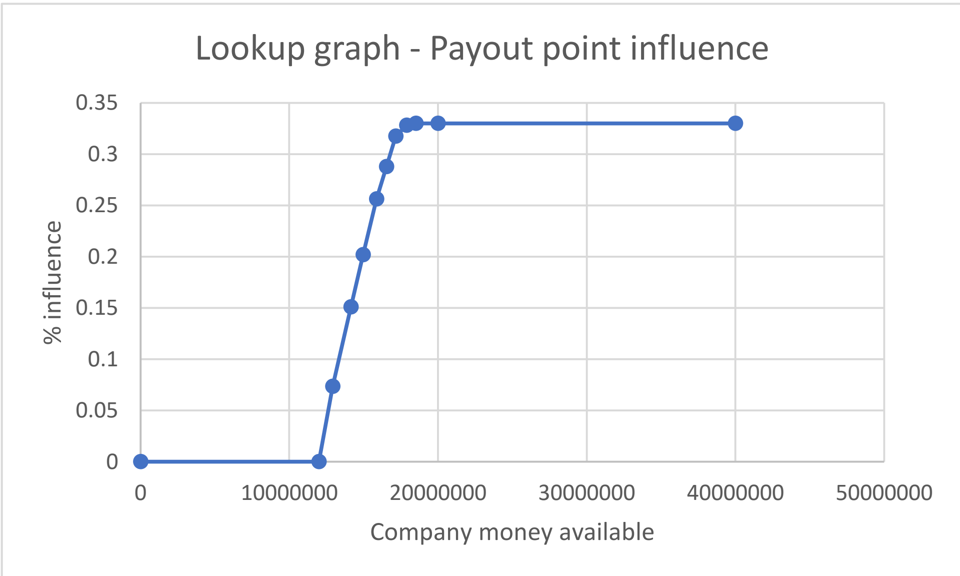


Figure A-0-25: Lookup graph – Pay out point influence

Crops grown lookup graphs

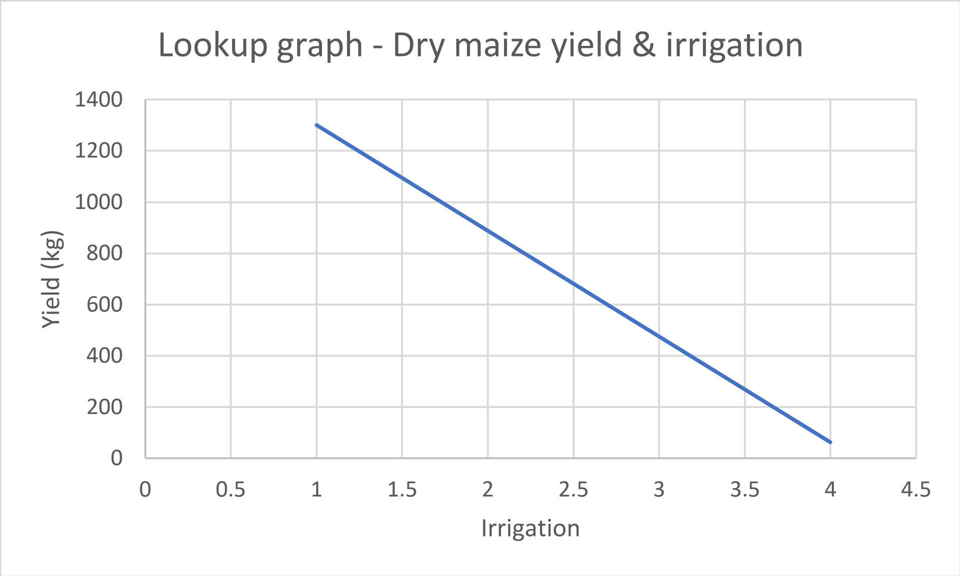


Figure A-0-26: Lookup graph - Dry maize yield & irrigation

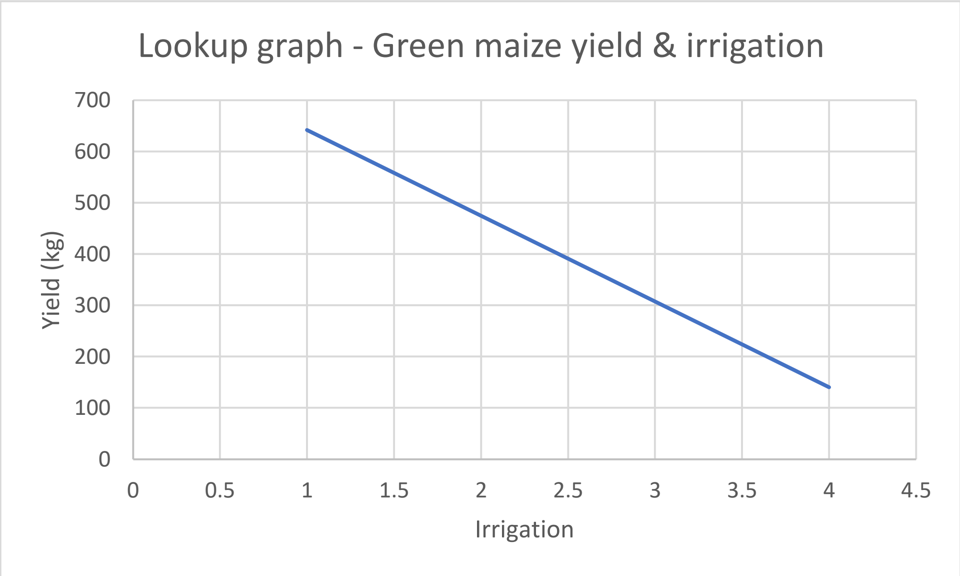


Figure A-0-27: Lookup graph - Green maize yield & irrigation

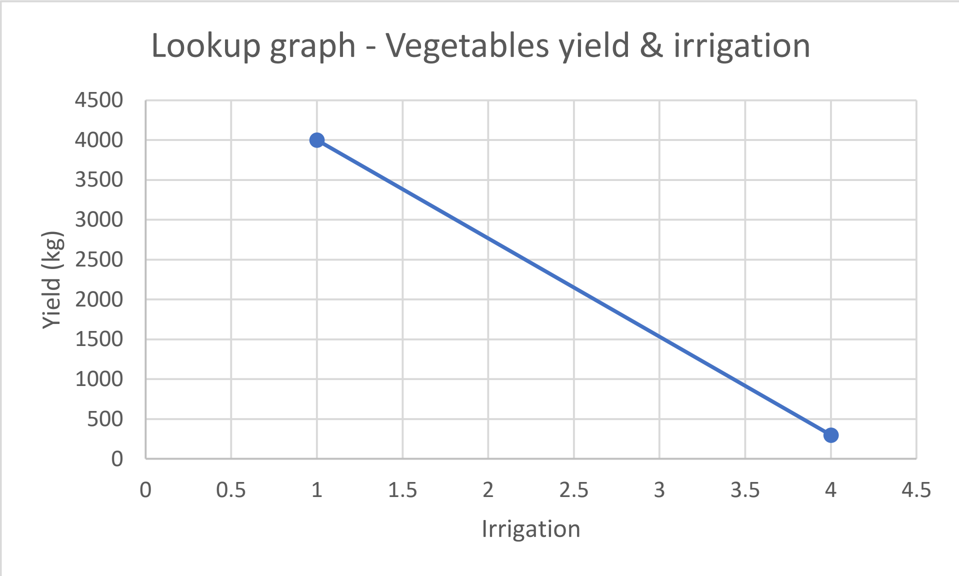


Figure A-0-28: Lookup graph - Vegetables yield & irrigation

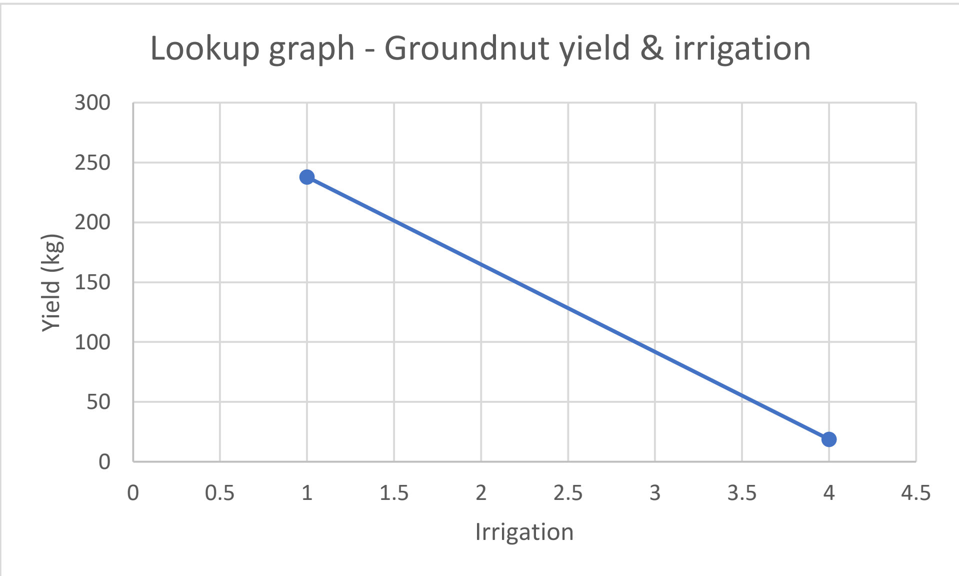


Figure A-0-29: Lookup graph - Groundnut yield & irrigation

Appendix E – Scenario planning extended

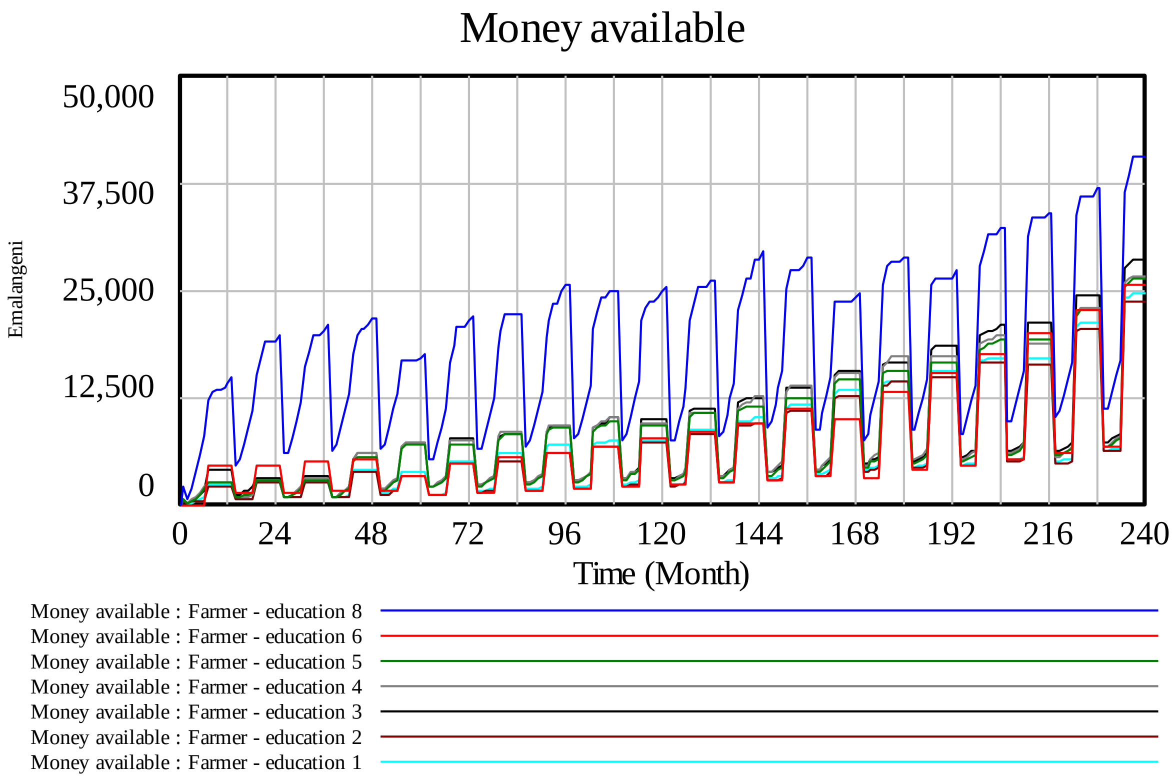


Figure A-0-30: Farmer that's educated - Money available

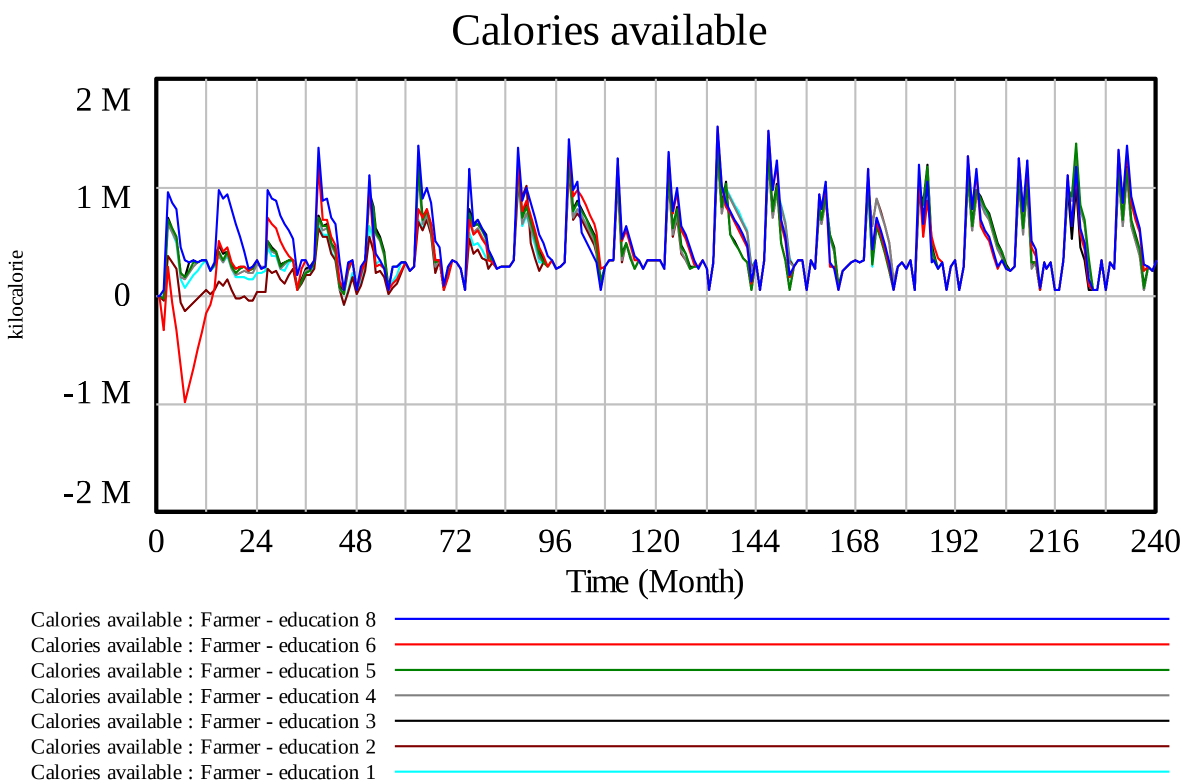


Figure A-0-31: Farmer that's educated - Calories available

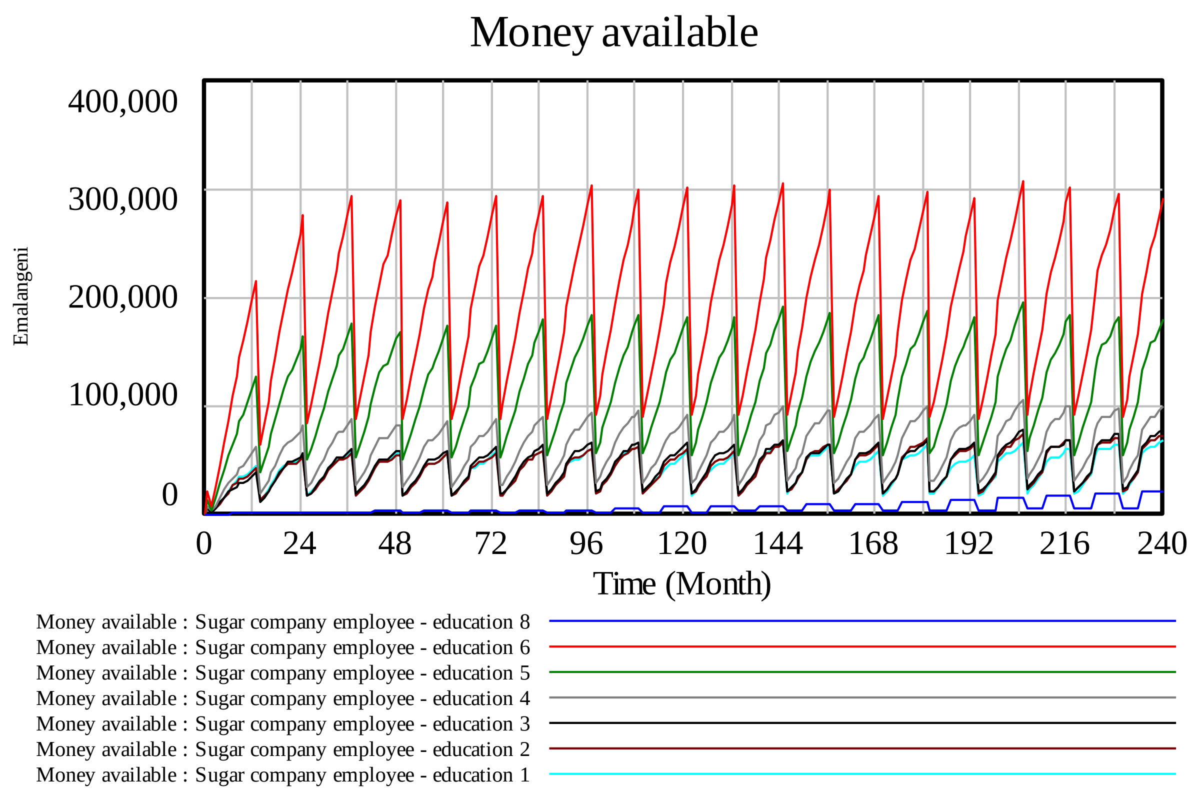


Figure A-0-32: Sugar company employee that's educated - Money available

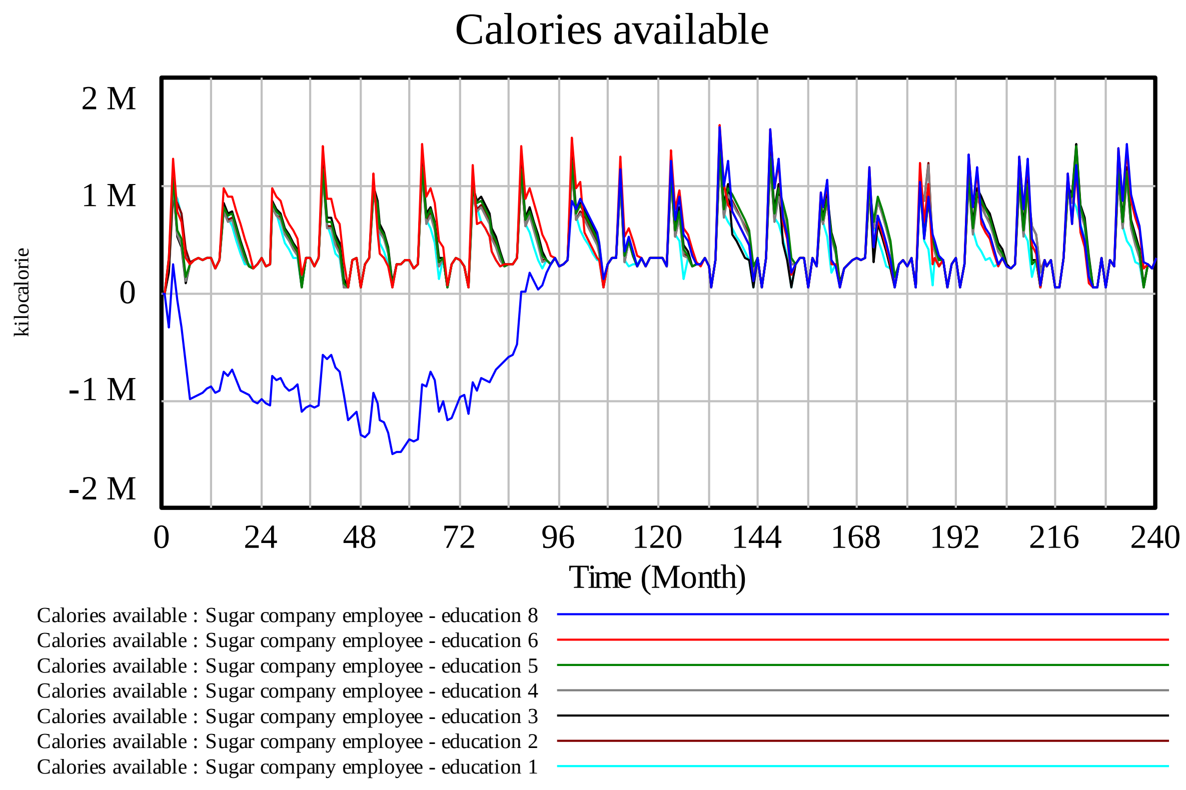


Figure A-0-33: Sugar company employee that's educated - Calories available

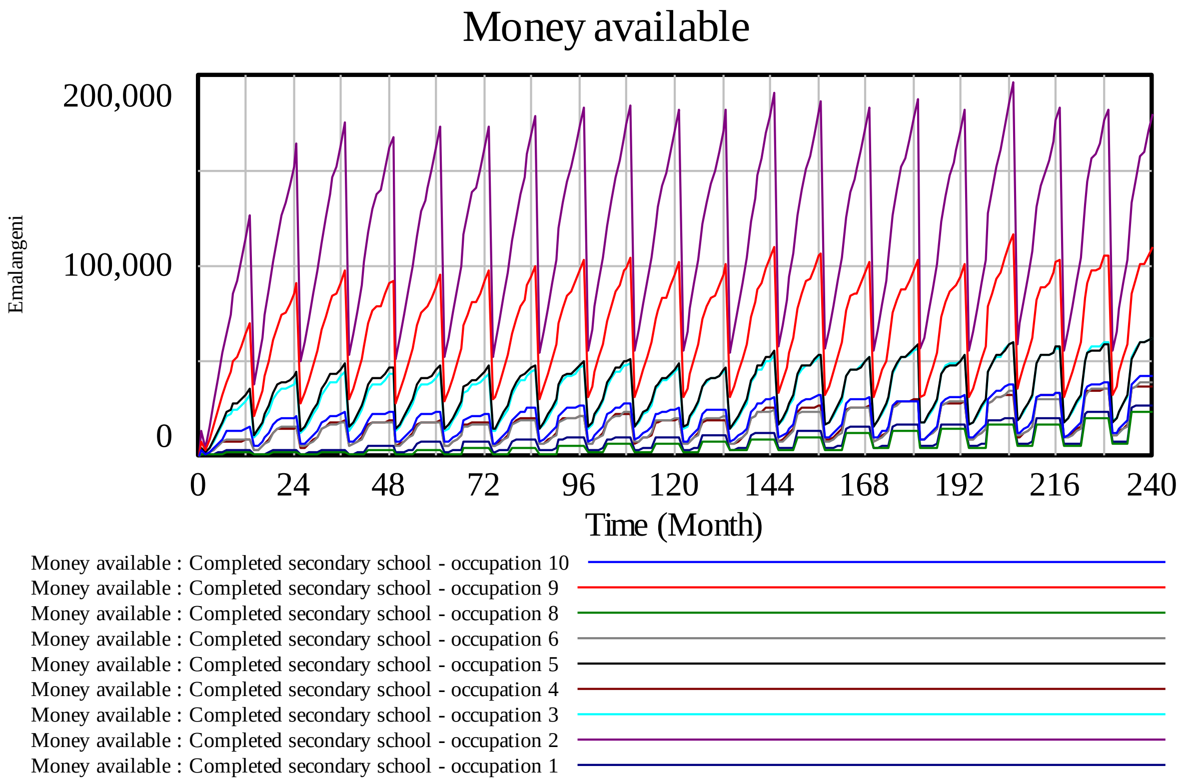


Figure A-0-35: Completed school what now - Money available

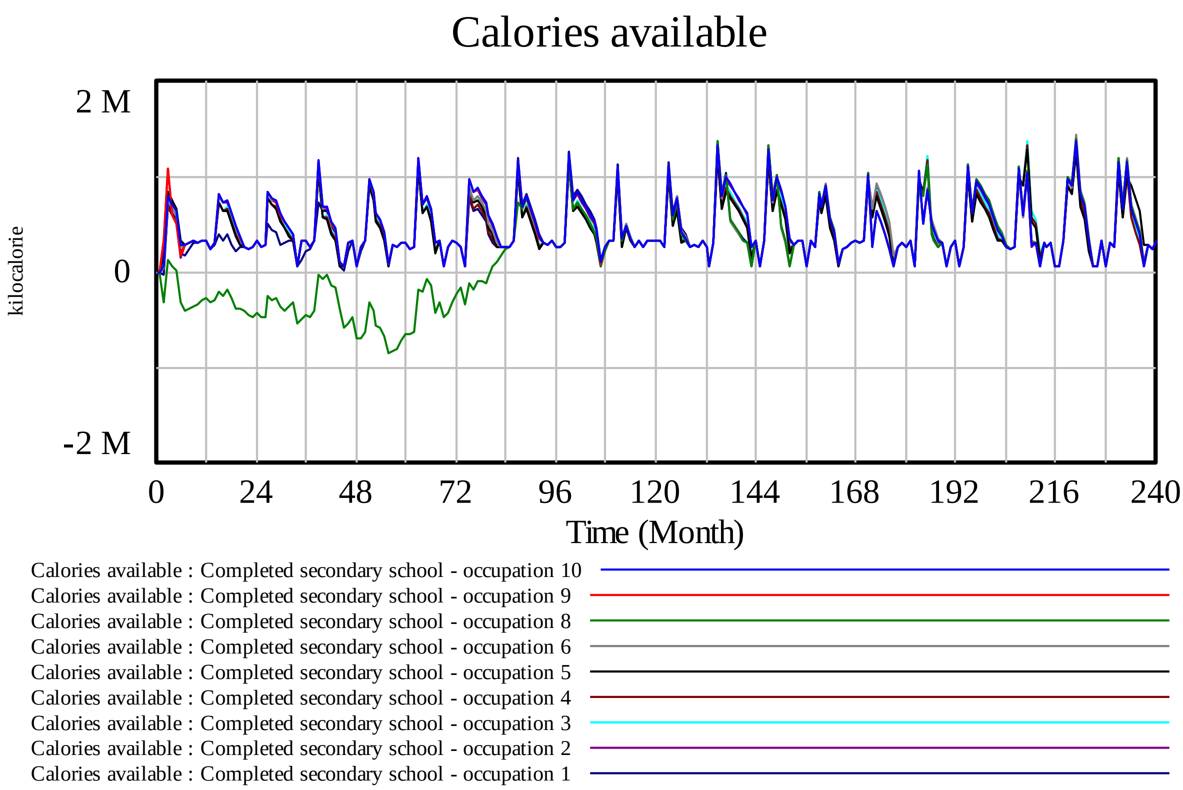


Figure A-0-34: Completed school what now - Calories available

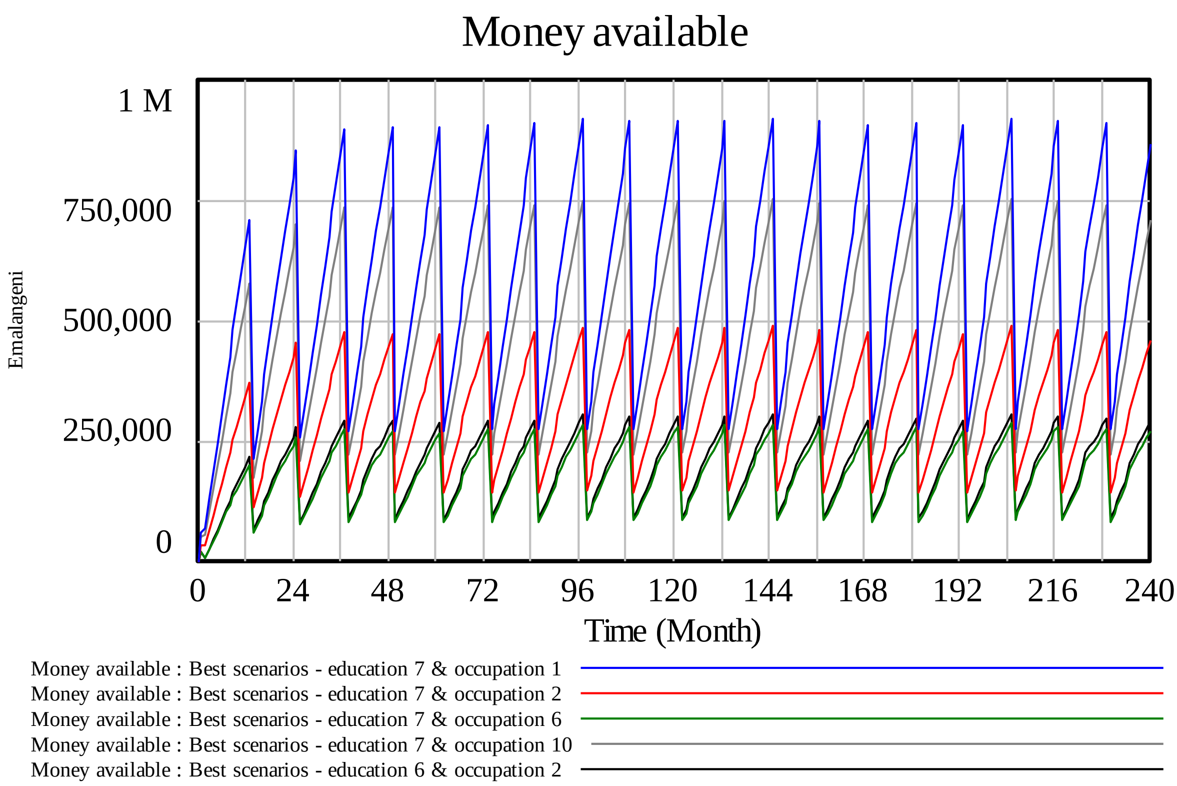


Figure A-0-37: Best scenarios - Money available

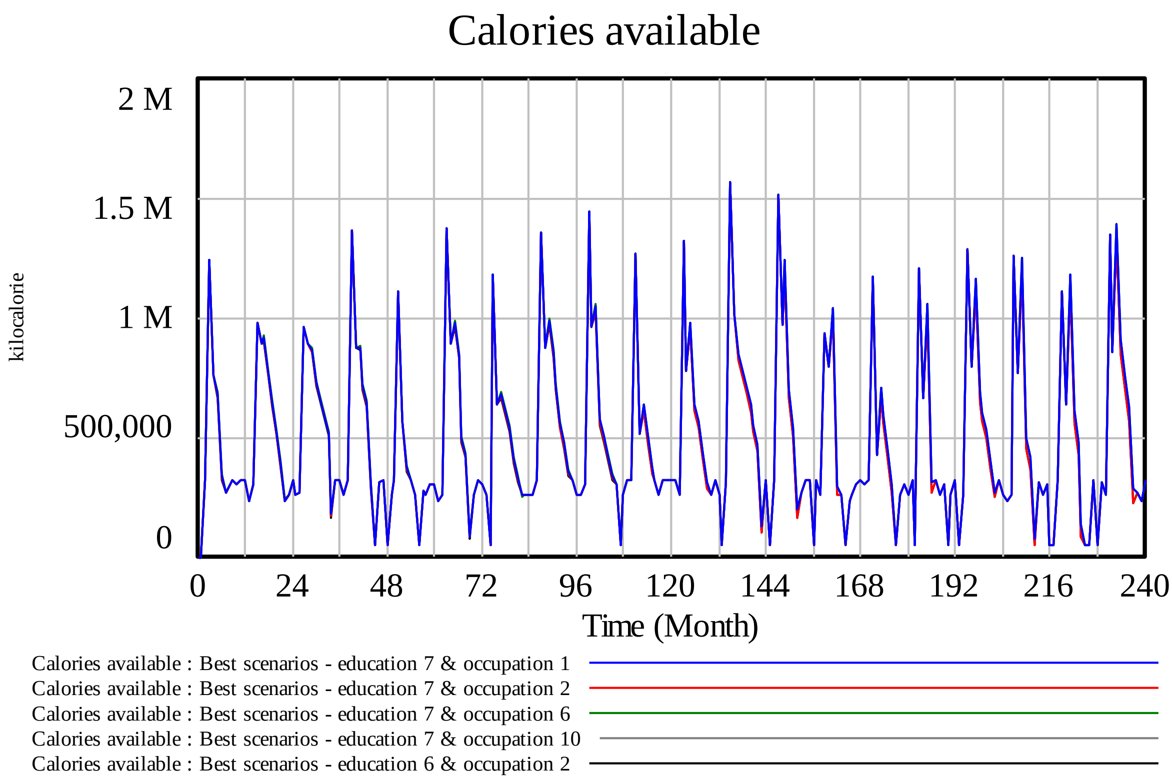


Figure A-0-36: Best scenarios - Calories available

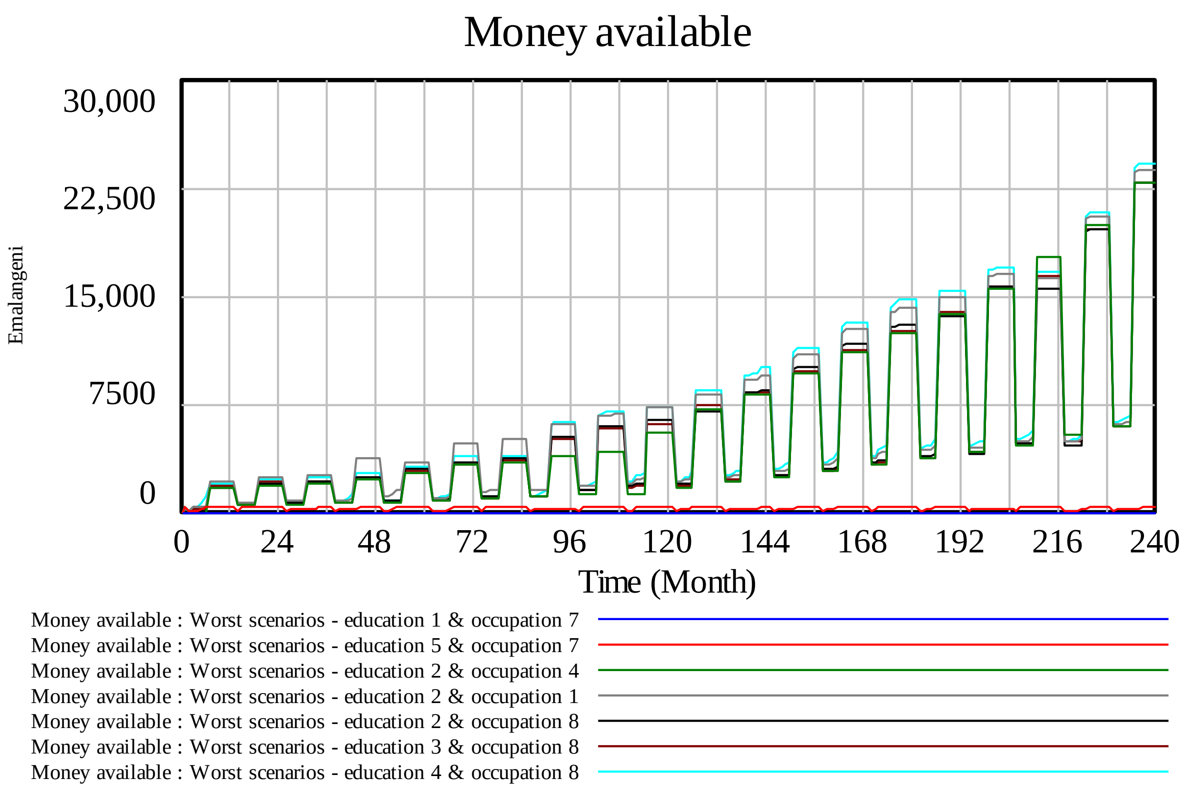


Figure A-0-39: Worst scenarios - Money available

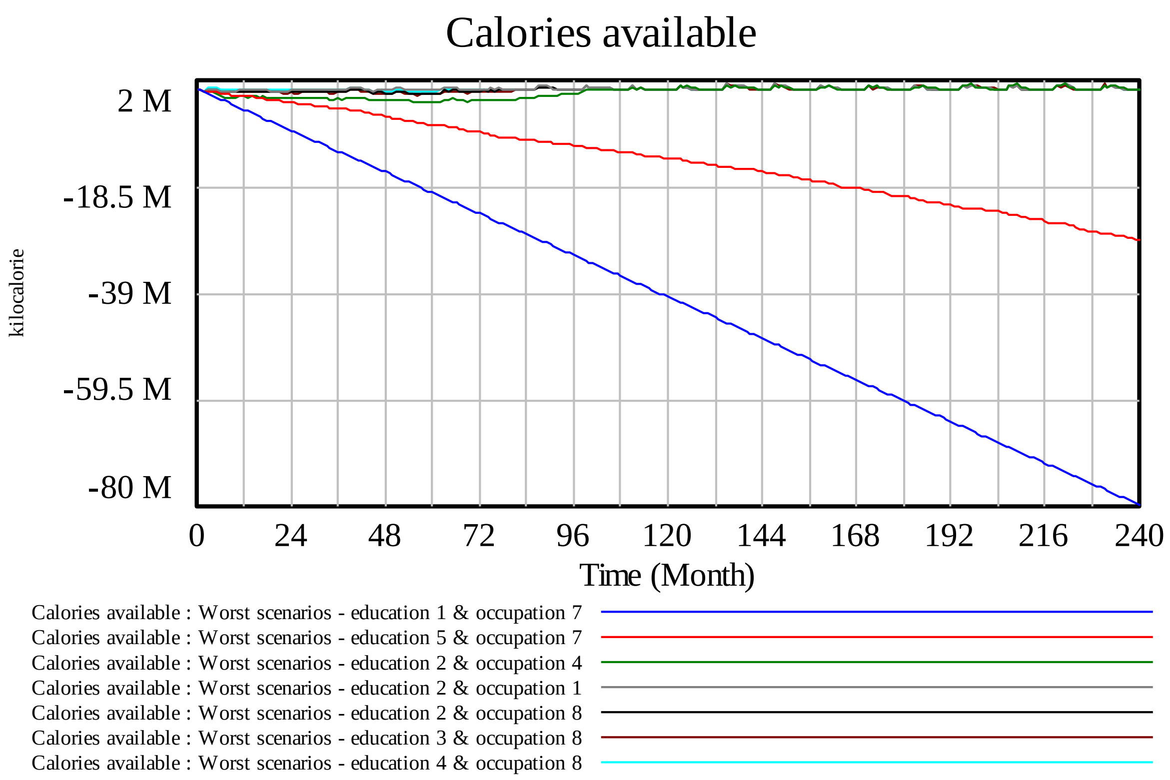


Figure A-0-38: Worst scenarios - Calories available