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Modeling household level food security with system dynamics: from crop decisions to food availability. A case study with subsistence farming in Zambia

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Resumo

A subnutrição ainda é um problema presente no mundo. No decurso dos últimos anos, registaram-se progressos na luta contra a desnutrição, mas um número inaceitável de pessoas ainda não dispõe dos alimentos necessários para uma vida ativa e saudável. A África Subsaariana continua a ser a região com a maior prevalência de pessoas subnutridas. Dentro da África Subsaariana, a Zâmbia é um dos países que enfrenta uma das maiores prevalências de níveis de subnutrição. Muitos estudos têm sido realizados para explicar a segurança alimentar e seus determinantes. No entanto, a segurança alimentar não é simplesmente uma função da produção ou da oferta, mas envolve várias dimensões, já que o sistema agrícola é complexo.

Esta pesquisa desenvolve uma abordagem baseada num modelo de dinâmica de sistemas para compreender e avaliar o sistema de agricultura de subsistência, tendo a Zâmbia como caso de estudo, sendo este um país que enfrenta uma alta prevalência de insegurança alimentar. O estudo contém uma avaliação dos fatores que afetam as decisões dos agricultores e outras relações importantes dentro do contexto de manejo na agricultura de subsistência. A abordagem de dinâmica de sistemas fornece informações valiosas sobre os elementos e diferentes condições que influenciam a segurança alimentar dos agregados familiares.

A segurança alimentar, na agricultura de subsistência, depende fortemente da decisão de quais culturas cultivar em uma época de cultivo. A avaliação destas decisões pretende melhorar a nossa compreensão deste processo e, desta forma, apoiar os agricultores na definição de estratégias para alocar recursos de forma mais eficiente. Portanto, quanto à identificação dos fatores que influenciam as decisões de colheitas, foram estudadas variáveis de três géneros de recursos (humanos, naturais e financeiros). Variáveis como disponibilidade de mão-de-obra, idade e sexo do chefe do agregado familiar, área de cultivo, nível de riqueza, fertilidade do solo, e distrito, influenciam as decisões dos agricultores. Além disto, a área de cultivo e a quantidade de fertilizante foram consideradas variáveis-chave no sistema de agricultura de subsistência e estão ligados a várias decisões.

O modelo de dinâmica de sistemas é uma estrutura complexa que contém diferentes setores, caracterizando cada uma das principais dinâmicas do sistema de agricultura de subsistência. Os setores representam as decisões de plantio, produtividade e produção, solo, decisões de vendas, receitas e despesas, e disponibilidade de alimentos, representando a dinâmica desde o início (decisões de plantio) até o final (disponibilidade de alimentos). Estas dinâmicas caracterizam-se por um conjunto de indicadores das principais variáveis de interesse, consideradas como os determinantes fundamentais da segurança alimentar dos agregados familiares.

A avaliação de cenários que representam diferentes tipologias de agregados familiares, demonstra que a dimensão do agregado familiar e sexo do chefe de família são dois fatores que influenciam fortemente a segurança alimentar do agregado familiar. As estratégias de proporcionar mais acesso aos fertilizantes para as famílias chefiadas por mulheres, e a implementação da agricultura de conservação, foram testadas como intervenções demonstrativas e indicam que são possíveis estratégias para aumentar a segurança alimentar.

Este estudo adotou uma abordagem que oferece uma ampla visão de um sistema, fornecendo significativamente mais informações do que meros modelos matemáticos que expõem apenas um tema específico de um sistema complexo. A pesquisa utiliza a metodologia da Dinâmica de Sistemas para avaliar a segurança alimentar, auxiliando a compreensão das circunstâncias e causas, e permite a avaliação de políticas e sua influência a longo prazo. Também foram identificadas as variáveis críticas que afetam o fenômeno da insegurança alimentar e como se comportam ao longo do tempo. Esta dissertação contribui para a adição de uma nova perspectiva sobre a tomada de decisão e conceção de políticas públicas. Os resultados demonstram o potencial desta abordagem única e, ao estruturar o conhecimento em um contexto mais amplo e dinâmico, contestaram as suposições convencionais.

Palavras-chave: segurança alimentar; decisões de plantio; dinâmica de sistemas; agricultura de subsistência.

Abstract

Undernourishment is still a present problem in the world. Progress have been made in the fight against malnutrition over the last years, yet an unacceptable number of people still lack the food they need for an active and healthy life. Sub-Saharan Africa is still the region with the highest prevalence of undernourishment people. Within Sub-Saharan Africa, Zambia is one of the countries facing one of the highest prevalence of undernourishment levels. Many studies have been carried out to explain food security and its determinants. However, food security is not simply a function of production or supply, it involves several dimensions, as the agricultural system is complex.

This research develops a system dynamics model based approach to understand and assess the subsistence farming system, taking Zambia as a case study, a country facing a high prevalence of food insecurity. The study contains an assessment of factors affecting farmers crop decisions and other important relationship within the subsistence farm management context. The system dynamics modeling approach provides valuable insights into the elements through which different conditions influences household food security.

Food security, in subsistence farming, strongly relies on the decision of which crops to plant in a growing season. Assessing these decisions intends to improve our understanding of this process and thus support farmers in defining strategies to allocate resources more efficiently. Therefore, regarding the identification of factors influencing crop decisions, variables of three different types of resources were studied (human, natural and financial). Variables such as labor availability, the age of the household's head and gender, farm land size, wealth level, soil fertility, and district, were found to influence farmers' crop decisions. Furthermore, farm land size and fertilizer were found to be key variables in the subsistence farming system, and are linked to several farm decisions.

The system dynamics model is a complex structure containing different sectors characterizing each of the main dynamics of the subsistence farming system. Sectors represent crop decisions, yield and production, soil, sales decisions, income and expenditure, and food availability dynamics, representing the dynamics from the beginning (crop decisions) to the end (food availability). These dynamics are characterized by a set of indicators of the main variables of interest, considered as the key determinants of household food security.

The evaluation of scenarios that express different household conditions, demonstrates that the size of the household and the gender of the households' head are two factors that strongly influence household level food security. The strategies of providing more access to fertilizer for female headed

households, and the implementation of conservation agriculture were tested as demonstrative intervention, and indicate that are possible strategies to increase food security.

This study has taken an approach that offers an ample vision of a system, providing significant more information than mere mathematical models that display only a specific subject of a complex system. It uses the System Dynamics methodology to assess food security supporting the understanding of events and causations, and allows the evaluation of policies and their long-term influence. It also identified the critical variables that affect the phenomenon of food insecurity and how they behavior over time. This thesis contributes to add a new perspective on the decision-making and policy design. The results display the potential of this unique approach, and structuring knowledge into a broader and dynamics context contested conventional suppositions.

Keywords: food security; crop decisions; system dynamics; subsistence farming.

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List of Acronyms and Abbreviations

FAO	Food and Agriculture Organization
CA	Conservation Agriculture
CAP	Conservation Agriculture Project
CFU	Conservation Farming Unit
CLD	Causal Loop Diagram
CSO	Central Statistics Office
EU	European Union
FAOSTAT	Food and Agriculture Organization Statistics
FEWS NET	Famine Early Warning Systems Network
FHH	Female Headed Household
FISP	Farmer Input Support Program
FRA	Food Reserve Agency
HLPE	High Level Panel of Experts
IFAD	International Fund for Agricultural Development
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IFRCRS	International Federation of Red Cross and Red Crescent Societies
LGP	Length of Growing Period
MHH	Male Headed Household
NEPAD	New Partnership for Africa's Development
PRP	Poverty Reduction Programme
SD	System Dynamics
SOM	Soil Organic Matter
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
WFP	World Food Programme
ZNFU	Zambian National Farmers Union

1. Introduction

1.1. About the topic

Undernourishment is still a present problem around the world. Progress have been made in the fight against malnutrition over the last years, yet an unacceptably number of people still lack the food they need for an active and healthy life. The latest available estimative indicates that around 795 million people in the world were undernourished in 2014-16. However, since 1990–92, the number of undernourished people has declined by 216 million globally, a reduction of 21,4% (FAO, IFAD, & WFP, 2015).

Undernourishment means that a person is not able to acquire enough food to meet the daily minimum dietary energy requirements, over a period of one year (FAO, 2015a). This value is expressed in per capita terms (kcal/person/day) and contains the amount of food energy that is needed for the human body to function at rest plus an allowance for light activity, and it is calculated for every country, taking into account parameters such as age, sex, height, and bodyweight. The latest estimation by FAO, calculated a minimum average of 1840 kcal/person/day for developing countries given their population structures in 2000 (FAO, 2006).

Therefore, an individual that habitually consumes below the minimum dietary energy requirement is considered undernourished, not eating enough to maintain health, body weight, and to engage in light activity. The result is physical and mental impairment (FAO, 2006). On the other hand, when an individual, at all times, has physical and economic access to sufficient safe and nutritious food, and meet the dietary needs and food preferences for a healthy and active life, is considered to be food secure (FAO, 1996).

Sub-Saharan Africa is still the region with the highest prevalence of undernourishment with 20% of the total population (220 million) being undernourished. Within Sub-Saharan Africa, Zambia is one of the countries facing one of the highest prevalence of undernourishment levels, with 47,8% of the population being undernourished in 2014-16. Moreover, this number have been rising with the increasing of the total population and little improvement in food security, from 2,7 million people undernourished in 1990-92 to the current 7,4 million (FAO, 2015a).

Most of the chronically food insecure and undernourished populations are smallholder farmers who have agriculture and food production as core business. This contradictory challenge is mostly due to the fact that smallholder farmers buy more food than they sell as they are not able to grow enough

food to feed themselves adequately throughout the year, and as a result make up about three quarters of the world's hungry and undernourished (Wiggins & Keats, 2013).

A smallholding is an agricultural holding run by a family using mostly their own labor and deriving from that work a large but variable share of its income. The family relies on its agricultural activities for at least part of the food consumed (through self-provision, non-monetary exchanges or market exchanges). The family members also engage in activities other than farming, locally or through migration. The holding relies on family labor with limited reliance on temporary hired labor, but may be engaged in labor exchanges within the neighborhood or a wider kinship framework (HLPE, 2013).

Globally, 84% of family farms are smaller than 2 hectares and manage only 12% of all agricultural land (FAO et al., 2015). The majority of smallholders live in poverty, and self-provision of food plays an important role of safety net for the household, and as an insurance against economic uncertainty. Smallholders are often in a permanent state of food insecurity, through insufficient self-provision of food and lack of access to purchased food due to limited income and deficient markets (HLPE, 2013).

Despite smallholders farming and producing food, their incomes are usually lower than average for their countries, rates of poverty are above average, and many households are vulnerable to hunger. It is estimated that the majority of people in absolute poverty live on small farms, as well as half the undernourished in the world, and for Africa, three-quarters of malnourished children (IFPRI, 2005).

Over the last years an unparalleled attention has been given to the importance of smallholder agriculture to the issue of food security (Dioula, H el ene Deret, Vachat, & Kiaya, 2013). A number of reports have outlined the pathways from smallholder agricultural development to improve food security and nutrition (UNCTAD, 2015; UNEP & IFAD, 2013; Wonder, 2014). Agricultural programs explicitly and specifically designed to smallholders, aiming to reduce malnutrition and increase food security, have great importance on increasing family welfare, and therefore the availability of food (UNEP & IFAD, 2013).

Many studies have been carried out to explain food security and its determinants. Food security is not simply a function of production or supply; it involves several dimensions with great influence on farmers and on the impoverished in particular (Applanaidu, Bakar, & Baharudin, 2014). The decisions concerning farming management, such as how to produce and use resources, are important determinants of food security (Upton, 1996). The impacts of farmers' choices in agricultural production can be felt in the different sectors of the agricultural system. Farm decisions determine household profits and well-being, land use, and capital requirements (Barlett, 1984).

Within this context, this study aims to provide a systemic assessment of household level food security, including the identification of factors affecting farm decisions and its impacts on food availability. This research intends to understand the subsistence agricultural system to better support farmers and policy makers, and allocate resources more efficiently. It also intends to fill the literature gap regarding the direct effect of crop decisions on the availability of food and farm welfare. The research is focused on the case of Zambia, a country facing a high prevalence of food insecurity.

1.2. Objectives and research questions

Factors that affect household food security in various developing countries, especially in Africa, have been documented in literature and these factors or determinants are most often than not location-specific, that is, different study areas were found to have variant attributes as food security determinants with diverse attributes (Aidoo, Mensah, & Tuffour, 2013). However, the usual approaches used to assess food security, based on mathematical models, and often assuming linearity and equilibrium, are not able to model the dynamics of a complex system characterized by non-linearity, multiple feedbacks, time delays, non-rationality, short term thinking and free rider agents. Most important, their findings are not easy to communicate to the broad non-academic audience of decision makers (Monasterolo, Mollona, & Pasqualino, 2015)

Furthermore, to understand the current reality of developing countries involving food crisis, poverty and political upheavals, we must look beneath generalizations about food production, rural instability, or economic development, and analyze how individual farmers make choices (Barlett, 1984). In subsistence farming, land use and crop choices are at the core of the decision-making process, and farmers encounter various physical and socioeconomic constraints, thus making land use decisions deserve careful consideration, as their consequences may extend the farm boundaries (Nguyen, Nguyen, Lippe, & Grote, 2016). Crop decisions directly affect the availability of food and capital, and the usage of resources and labor.

Therefore, understanding the determinants of land use and crop diversification decisions, made by small farm holders, provide useful information for the promotion of food security and the fight against poverty. It can also support designing rural development programs tailored to those farmers to improve their livelihoods.

The objective of this research is to develop a system dynamics modeling approach for studying the subsistence agriculture system, considering farmers' decisions, especially the ones involving crop choices. The methodological approach aims to deepen the understanding of the structure and main feedbacks associated with subsistence farming and its implications in household level food security.

Furthermore, the research aims to explore the development of strategies to increase food security in developing countries.

Firstly, the study aims to identify factors influencing smallholding farmers' crop decisions and other important relationships through statistic tests, and secondly to integrate these findings into a system dynamics model intending to assess its effects on the household availability of food. The analysis takes place in Zambia, a Sub-Saharan country facing a high prevalence of undernourishment people with little improvement in food security, and lack of progress towards international targets for food security. The research intends to contribute and provide information to policy makers responsible of defining strategies to combat food insecurity and undernourishment.

The central questions guiding the current research are:

- What are the factors that influence smallholding farmers crop decision?
- What are main relationships involved in subsistence farming?
- What is the structure and main feedback loops that explain the food security phenomenon in subsistence farming?
- What are possible strategies that can be adopted to diminish food insecurity in subsistence farming?

Answering these questions brings a new perspective to developing of strategies concerning small holder farmers. Creating a causal structure with relationships of the different elements involved in the subsistence farming, starting from crop decisions and concluding with food availability, is expected to provide a new method for analyzing and presenting the causes of food insecurity. This research intends to identify smallholding farmers' strengths and weaknesses, and provide a visual tool for conveying the information to the political, economic, and social sphere.

Integrating the information of farmers' decisions into a system dynamics model is expected to fill the gap in the literature concerning the effects of such decisions in the household availability of food. It can allow researchers and policy makers to tailor policies based on the specific needs of the small holding farmers. This thesis explores the causal structure of the availability of food and develops scenarios which show both the model's possibilities as well as answer to existing questions about the dynamics of small holder farms. The present study facilitates both the assessment of the advances made and the clarification of future research needs.

1.3. Organization of the thesis

The thesis is structured in six main chapters:

- 1) **Introduction** - Consists of a framework of the research, underlying the food security problem in the world and sub-Saharan Africa. It also describes the terms food security, undernourishment, and small holding farm. Furthermore, it contains the objectives and research questions, and a synthesis of the thesis organization and contents.
- 2) **Literature Review** - Presents the academic literature and theoretical principles of the topics in study. It contains an introduction to Zambia, and relevant information about the country's economy, as well as an overview of the Zambian most important crops, and fertilizer sector. The main concepts and fundamentals to assess farmers' decisions are described, as well as the usual approaches. Lastly, the common methodology to assess food security is described, including usual approaches, and the system dynamic approach.
- 3) **Methods** – Presents the methodology used in each stage of this research, including the statistical tests used for the identification of decision determinants, and a description about the model building process and scenario analysis.
- 4) **Identification of Decision Determinants** - This segment contains relevant information about the statistical analysis, including information about the data collection and descriptive statistics. It also presents the statistical analysis results that identified factors influencing crop decisions and other important relationships.
- 5) **Dynamics of Subsistence Farming System: The Zambia Case Study** – The system dynamics model is described, including its sectors and main structure, followed by the presentation of indicators to assess food security, and the model validation. Casual loop diagrams are then presented to display the main feedback structure of the system. The two final sections consist of the scenario analysis, and the policy design aiming to increase food security.
- 6) **Conclusion** – The final chapter presents the conclusions, including a critical review of the developed work and the obtained results. It also contains suggestions for future research.

2. Literature Review

2.1. Assessing Farmers' Decisions

Assessment means judgement, appraisal, estimation or evaluation. It is a process that is used to understand a situation in order to make decisions. The assessment must collect information that will allow a good analysis of the situation and the threats to life, human dignity, health and livelihoods of the population. The principle of an assessment is that the affected community and local authorities are consulted. Assessments are used as a tool to design, monitor, or evaluate a program (IFRCRS, 2006).

In the subsistence conditions typical in many regions of Sub-Saharan Africa, crop productivity has an important influence on food security (Ringler, Zhu, Cai, Koo, & Wang, 2011). It both contributes directly to household food availability, as well as influencing incomes, local food prices and farmers' ability to invest in other cropping, farming, and livelihood activities (Vermeulen et al., 2012). Therefore, despite the complexity and uncertainty associated with farming systems and food security, there is an urgent need for science to support decision making at all levels (McIntyre, Herren, Wakhungu, & Watson, 2009).

Farmers' practices reflect their particular aims and constraints (Capillon, 1986). Understanding the reasons and wherefores of these practices is regarded as a necessary step towards designing new agronomic techniques (Gibbon, 1994). In this kind of research, farming practices are seen as the result of a farmer's direct intentions; to analyze them, one must look at the underlying decision-making processes, which act as a sort of driving force for the practices (Papy, 1994).

In Sub-Saharan Africa, more than 95% of the farmed land is rain-fed (Wani, Sreedevi, Rockström, & Ramakrishna, 2009), and nearly 90% of staple food production will continue to come from rain-fed farming systems (Rosegrant, Cai, & Cline, 2002). In most Sub-Saharan countries, the precipitation patterns allow only one harvest of staple crops per year. Therefore, post rainy and summer crops need supplemental irrigation (Krishna, 2013), however, only 3,7% of the arable land in Sub-Sharan Africa is irrigated (African Union & NEPAD, 2002).

For rain-fed agriculture in Africa, water availability is the main constraint that limits the time during which crops can grow. This period of favorable conditions is named the length of growing period (LGP), and the variation of the water availability can, in dry years, result in crop failure, when the LGP does not fulfill the demands of the crop to complete its crop cycle (Vrieling, De Leeuw, & Said, 2013).

Farmers must select their crops carefully to both optimally use the growing period, while reducing the risks of not meeting the crop demands in specific years. At the same time, climate change can bring about shortening or lengthening of the LGP (Gregory, Ingram, & Brklacich, 2005), narrowing the range of crops that can be cultivated in a region. Therefore, the food security of African subsistence farmers and farming systems strongly depends on the crop choice, the year-to-year LGP variability, and longer-term trends in LGP (Sarr, 2012).

Given that the food security in a small holding farm strongly relies on the decision of which crops to plant in a growing season, assessing these decisions is intended to improve our understanding of this process (Upton, 1987), and thus support farmers, policy makers and other stakeholders in defining strategies to allocate scarce and competing resource more efficiently, as well as design policy options and anticipate their effects at different time scale horizons (Dury, Schaller, Garcia, Reynaud, & Bergez, 2011).

The multiplicity of factors which affect the variation of farmers' decisions in choosing distinct crops have been largely attributed to the differences in physical factors, especially soils, climate, and topography. The bias towards physical relationships has resulted from a lack of socio-economic data about the farmers themselves, so that little is known about the importance of the socio-personal circumstances as a factor in the decision-making process (Ilbery, 1977).

The motives of farmers are very varied and whilst agriculture is primarily an economic activity, governed by the movements of production and prices, however, the decisions are not always based on economic considerations alone. Therefore, when studying agricultural decision-making, one should not consider physical or economic factors in isolation from a wide range of socio-economic and environmental factors which have a direct impact on farmers' decision (Barlett, 1984).

Tarrant (as cited in Ilbery, 1978) recognized three possible approaches to the theoretical study of agricultural decision-making: the first assumes that the physical environment controls agricultural decision-making; the second is related to economic influences, where uniform producers react in a uniform and rational manner to economic circumstances; and third recognizes a further set of influences including the values of individual farmers, identifiable aims and attitudes towards risk aversion, which are all important in final decisions about agriculture.

The choice of crops is at the core of the farming management (Nevo, Oas, & Podmore, 1994). A suitable cropping plan must satisfy different objectives, and take into account several factors (Nevo & Amir, 1991). A cropping plan refers to the acreages occupied by all the different crops every year (Wijnands, 1999). Crop acreage is the area on a farm usually devoted to one or a group of crops every

year (e.g. x hectares of maize, y hectares of cotton) (Rounsevell, Annetts, Audsley, Mayr, & Reginster, 2003).

Another important concept is the cropping plan decisions, which are crucial in crop production processes and have considerable effects on productivity (Nevo & Amir, 1991). Cropping plan decisions are the primary land-use decisions in farming systems and involve, at the very least, the choice of crops to be grown, their acreage and their allocation within a particular farmland (Nevo et al., 1994). Farmers weigh up the objectives and constraints to make a decision suited into different spatial and temporal dynamics (Aubry, Papy, & Capillon, 1998).

The extensive literature on this subject reflects the complexity of the decision-making process regarding cropping plan decisions. In this field, the factors that influence different choices is a significant theme and presented in numerous studies.

Physical factors such as the quality of the soil, the availability of water, and land declivity are extensively evidenced to affect cropping plan decisions, e.g. (Cutforth, Francis, Lynne, Mortensen, & Eskridge, 2001; Talawar & Rhoades, 1998). However, there are fields less explored in this theme, as socio-personal factors, which were also recognized to influence farmers decisions, e.g. (Ryder, 2003). As well as cultural factors, such as agricultural traditions, and age at which the farmer learned agriculture, e.g. (Velásquez-Milla, Casas, Torres-Guevara, & Cruz-Soriano, 2011).

Moreover, financial aspects also affect cropping plan decisions. For instance, a decrease in the cultivation of cowpeas in Haiti due to their widely fluctuation price was observed (Jaffe, 1989). Nevertheless, economic elements might not always be highly influential. Due to the limited commercial nature of agriculture in Tanzania, factors such as the projected market price and the amount of money required to grow were not significant for decision-making process underlying crop plan decisions, but factors related to household consumption and survival, and security of food supply proved to be important (Briggs, 1991).

Additionally, studies engaging a behavioral approach analyzing crop selection have considered the individual preferences of the farmer and his or her household. Factors as the amount of free time allowed by the crop, knowledge of the farmer, influence of others, preferences of taste, and the experience of the farmer with specific crops, were found to lead decision making, e.g. (Briggs, 1985; Ilbery, 1977).

The characteristics of the crop, e.g. cycle of growth, the capacity to resist pests, and harvest dates were also suggested to influence crop decision. Many crops have specific pests, diseases, and fertility

requirements, making the cultivation and production of the crop difficult or overly risky. For instance, in Haiti, farmers started growing less yams in several regions due to declining fertility, and rising levels of grub and nematodes infestations (Jaffe, 1989).

Furthermore, the availability of resources influence crop selection, including extension services provision, the availability of fertilizers, herbicides pesticides, and crop spraying, as well as machinery (Greig, 2009).

Lastly, cropping plan decisions can be taken differently according to the type of farm. For instance, Zambian agriculture has three broad categories of farmers. Small-scale farmers (76% of the farmer population) that produce staple foods with an occasional marketable surplus, medium-scale farmers that produce maize and a few cash crops for the market, and large-scale farmers that produce various crops for the local and export markets (Aregheore, 2006).

Extension services to help farmers decide what and when to plant, how to prepare for planting and best practices related to growing, dealing with pests and disease, harvesting, and post-harvest practices such as packing and storage (USAID, 2011). An example of such extension service is the USAID program that enhances Information and Communication Technology (ICT) throughout sub-Saharan Africa, thus facilitating the broadcasting of weather conditions, information on farming cycles, market prices, and therefore influencing farmers' choices.

In most African countries, many farmers rely on external agents to support production due to endogenous constraints (e.g. small scale production, poverty, high illiteracy, ill-health) and exogenous constraints (e.g. lack of infrastructure, poor access to credit) (Berthe, 2015).

In Zambia, the program Feed the Future covers five districts and, within all that it provides, helps households to more efficiently manage their resources and support decision-making over food and cash-crop farming, livestock, and fisheries, and autonomy in agricultural production (United States Agency for International Development, 2013).

Researchers have used several different statistical methodologies to analyze factors influencing farmers' cropping plan decisions, such as linear regressions and correlations (Nyanga, 2012; Velásquez-Milla et al., 2011), point score analyses (Greig, 2009; Ilbery, 1977), logit models (Carpentier & Letort, 2009; Wood, Jina, Jain, Kristjanson, & DeFries, 2014), and count data models (Isgin, Bilgic, Forster, & Batte, 2008). As well as a qualitative analyze of interviews (Jaffe, 1989).

Given the large number of aspects that can influence cropping plan decisions, the present study seeks

to identify the underlying factors which explain farmers' decisions in Zambia.

2.2. Assessing Food Security – Levels and Approaches

Continuing population and consumption growth will mean that the global demand for food will increase for at least another 40 years. Growing competition for land, water, and energy, in addition to the overexploitation of fisheries, will affect our ability to produce food, as will the urgent requirement to reduce the impact of the food system on the environment. The effects of climate change are a further threat (Godfray et al., 2010).

The complexity of factors contributing to food security and the importance of context in interpreting these factors has led to some institutions prioritizing consultative methods for developing food security measurement tools (Jones, Ngure, Pelto, & Young, 2013). Many studies have been carried out to explain food security and its determinants. Food security is not simply a function of production or supply; it involves several dimensions with great influence on farmers and on the impoverished in particular (Applanaidu et al., 2014).

Food security assessments look at how people try to maintain a secure food environment and whether they succeed. The general objective is to understand how severe the food insecurity is, and why this is the case. Then the objective is to determine if there is a need to intervene to return people to a normal food security situation in the short term and/or long term. In addition, food security assessments can help to predict upcoming food insecurity or can predict the duration of an insecure food period. It is important to understand how people make their living, how they meet their food needs, what resources they have available, and who can access these resources and whether this access changes over time (IFRCRS, 2006).

Food security can be analyzed at different levels: national, household, and individual (**Figure 1**). At national level, food security is described as a satisfactory balance between food demand and food supply at reasonable prices. Households are identified as food secure if their entitlements, or demand for food is greater than their needs, defined as the aggregation of individual requirements. An individual is food secure if his or her food consumption is always greater than need (Thompson & Metz, 1998). These levels interact between each other, making food security a complex system to analyze.

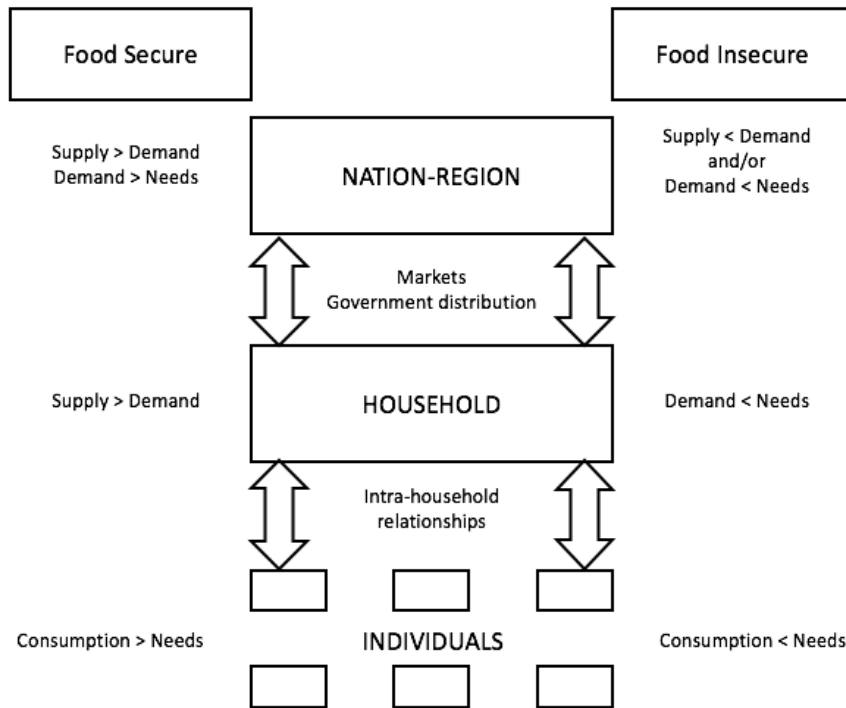


Figure 1 – Levels to assess food security (Source: Thompson & Metz, 1998)

Measuring food security may focus on food availability, access, utilization, the stability of food security over time, or some combination of these domains. These metrics may draw from data at national, regional, household, and/or individual levels. Such tools may vary from simple indicators for which data can be quickly collected and easily analyzed to comprehensive measures that require detailed, time and resource-intensive data collection and sophisticated analytic skills to yield results. Food security measures may rely on data from hypothesized determinants of food security (e.g., the price of commodities) or on data from purported consequences of food security (e.g., child malnutrition) (Jones et al., 2013).

During the last decades, researchers and institutions have used models for projecting and predicting global food security, focusing on food supply and demand, and variables related to the food system at different levels. MacCalla & Revoredo (2001) reviewed several models related to food security and stated that the methodology used to develop most of the projections and predictions relies on correlated models. Such methodology is controlled mainly by data and do not give insights into the causal relationships in the system, implying that what matters in these models is their aggregate behavior, which is independent from the characteristics of their internal structure.

The high complexity of food security is due to several factors, including the lack of tools or methodologies capable of assessing the effects of long-term policies in the system, actors' failures in playing proper roles in the system thus acting under different influences and pressure, the lack of a

holistic system model to facilitate intervention and understanding the system, the high causality between different contexts such as the socio-economic, political and environmental development, performance of the food economy and practices related to the health sector (Saeed, 1994).

2.2.1. National Level

Several institutions have measured food security at the national level, such as FAO and FEWSNET. These measures developed for use at the country level often emphasize food availability. Tools for measuring food availability, such as food balance sheets, have traditionally drawn from nationally aggregated data on food supply (i.e., total amount of food produced and imported) and utilization [i.e., the quantity of food exported, fed to livestock, used for seed, processed for food and non-food uses, and lost during storage and transportation (FAO, 2001b)] These data are used to create FAO's core food security measure, the prevalence of undernourishment (Jones et al., 2013).

The Global Food Security Index (GFSI) is another multi-dimensional tool for assessing country-level trends in food security. It was designed by the Economist Intelligence Unit and uses a total of 30 indicators within 3 domains of food security, affordability, availability, and quality and safety, to provide a standard against which country-level food security can be measured (Economist Intelligence Unit, 2012).

Similar to other national-level metrics, the GFSI ranks the performance of countries in achieving food security, using quantitative and qualitative indicators that reflect not only food availability, but food access (e.g., food consumption as a proportion of total household expenditure, proportion of population living under or close to the global poverty line, food prices) and diet quality (e.g., dietary availability of micronutrients) (Jones et al., 2013).

National-level food security estimates may be viewed as yardsticks for cross-national comparisons and monitoring changes in macro-level trends. However, the types and sources of data used, the assumptions made when calculating food security, and the intended purpose of different measures will inform the accuracy and interpretation of results (Jones et al., 2013).

2.2.2. Household Level

National-level measurement tools do not emphasize household level behaviors and determinants of food access because of their focus on national or regional-level estimates and trends, thus household-level measures of food security are concerned with food security dynamics between and within households. These measures rely on data from household surveys, they are able to more accurately capture the "access" component of food security than measures that rely on nationally aggregated data

(Jones et al., 2013).

At the household level, FAO has used household consumption and expenditure surveys (HCESs) (Committee on World Food Security, 2011) that measure poverty (i.e., monetary expenditures as a proxy for income) and assess consumer price indices and socioeconomic status (e.g., education, housing type/quality, assets, health-seeking behavior, income) to examine patterns of food and nonfood consumption among households (Fiedler, Carletto, & Dupriez, 2012). However, these data may provide widely varying estimates of household food consumption that will not provide sufficiently accurate estimates for some purposes (e.g., monitoring the food security status of the same households over time) (Jones et al., 2013).

One method used to assess food security at household level is the item response theory model called the Rasch model. The Rasch model consists in a mathematical model to evaluate responses of a survey and provides a theoretical base and a set of statistical tools to assess the suitability of a set of survey items for scale construction, create a scale from the items, and compare performance of a scale in various populations and survey contexts. It has been used widely as the statistical basis for survey-based experiential food security measurement (Nord, 2014).

Researchers have used the Rasch model to assess household food security in several studies. Hackett, Zubieta, Hernandez, & Melgar-Quiñonez (2007) used the model to examine the relationship between household food insecurity and household food supplies in Ecuador. Rafiei, Nord, Sadeghizadeh, & Entezari (2009) measured food insecurity of household-level adult and child in Iran through a similar approach. Owino, Wesonga, & Nabugoomu (2014) used the Rasch model to analyze food security dynamics in Uganda, based on items that were believe to affect food security such as money income.

However, the Rasch model has limitations and does not cover all potential household food insecurity experiences as it concentrates on perceptions, attitudes, and feelings. It does not allow gender, household or demographic characteristics, and their interactions as covariates in the model when computing individual household food security scores. The effects of such factors on food security are therefore not estimated (Owino et al., 2014). Furthermore, assessing food security using Rasch model based approaches, does not allow an evaluation over time.

Estimating of what drives the incidence of food insecurity is just as important as measurement of food security (Matchaya & Chilonda, 2012). For this purpose, logistic regressions have been used to examine the determinants of food security among households. This statistic approach is used to recognize relationship between a response variable and one or more explanatory variables (Hosmer Jr & Lemeshow, 2004).

Aidoo, Mensah & Tuffour (2013) used this approach in a research in Ghana and found variables such as household size, credit access, and marital status to be a significant influence in the household food security. Larger households were found to be food insecure compared with households with smaller sizes. Mannaf & Uddin (2012) found similar results, plus the age of the household head was found to influence food security. Zakari, Ying, & Song (2014) found factors such as labor supply, access to market, and distance away from a main road, to be significant influences for a household to have enough daily rations.

However, the dichotomous nature of logistic model, can mask important information leading to a significant loss of statistical precision (Fedorov & Wu, 2007). Deriving conclusions from carefully chosen food security agents would be more useful than relying solely on a single agent (Matchaya & Chilonda, 2012).

2.2.3. System Dynamics Approach to Assess Food Security

A more recent approach for modeling projections in food security is the System Dynamics method. System dynamics is a problem-oriented multidisciplinary approach that allows to identify, to understand, and to utilize the relationship between behavior and structure in complex dynamic systems. The underlying concept of the System Dynamics implies that the understanding of complex system's behavior can only be achieved through the coverage of the entire system rather than isolated individual parts (Colin, 1997).

System dynamics models have been applied to different areas of studies, such as global dynamics, energy, business, and economics (Monasterolo et al., 2015). System dynamics can be applied to any dynamic system, with any time and spatial scale, and it has the ability to understand how the behavior of a system arises from the interaction of its agents over time, discover and represent feedback process, and identify stock and flow relationships (Sterman, 2000).

System dynamics models are based on a set of discrete difference equations, i.e., differential equations with a fixed time step because that is recursively solved, where the current state of a variable depends on the previous system state. Through these equations, it is possible to describe, analyze and simulate the macro-level behavior of complex adaptive systems (Monasterolo et al., 2015). System dynamics can be defined as a set of stocks changing through the flows which characterize them. Stocks can be discrete quantities representing homogeneous groups of well mixed elements. Flows represent the movement of agents between homogenous groups. In this way, stocks offer an aggregate representation of the system components (Sterman, 2000).

System dynamics models belong to the family of simulation models, that is, models that mimic the behavior of the system they attempt to reproduce and its functional relationships, differing from econometric or fully analytical models that only aim at approximating the reality to an average form which answers some assumptions in order to reach the desired result (Monasterolo et al., 2015).

Introducing the system methodology to food security models supports the understanding of events and causations, and allows the evaluation of policies and their long-term influence. Such models can be designed to allow the user to analyze and manipulate its internal structure as well as to study the relationship between the structure and the behavior of the model. The simulation of system dynamics models is more explicit considering the assumptions on how variables interact with each other. It allows to identify the critical variables that affect a phenomenon, how they face induced changes and their behavior over time, encouraging the development of more probable scenarios (Giraldo, Betancur, & Arango, 2008).

As system dynamics models are able to reveal which factors most influence a phenomenon, making it appropriate for policy evaluation, they make a great contribute for food security studies. Table 1 presents a review of system dynamics models related to food security. For each model, it was identified the research objective, model's purpose and description.

Table 1 – Review of system Dynamics models assessing food security

Authors	Country	Research Objective	Model's Purpose	Model Description
Bala, Alias, Arshad, Noh, & Hadi (2014)	Malaysia	Attempting to rectify problems paddy rice production, soil fertility, and agriculture development by proposing the need for more research and development for higher yielding varieties, application of bio-fertilizers and new approach of extension (through farmer field schools).	To understand and design policy for increasing local productivity and reducing field level productivity gaps, and address the questions of withdrawal of fertilizer subsidies and gradual transition to bio-fertilizers using systems approach.	The model demonstrates how can research and development, subsidies and training increase productivity positively affecting the rice production and thus food security.
Bala & Hossain (2010)	Bangladesh	Based on the production of shrimps in Bangladesh, the objective of this research to simulate integrated coastal zone management systems for sustainable development and determine the management strategies for sustainable development of the coastal zone system.	To study the dynamics of the coastal zone for a sustainable management of food production, ecology, and environment aiming to alleviate the poverty of coastal population and ensure food security. To support policy planners to assess different policy issues and to design a policy for sustainable development in Bangladesh	The model is divided in three sectors: food security, ecological footprint, and bio-capacity. It demonstrates a feedback between food availability, and ecological footprint. Showing the importance of a sustainable development to increase food security.
Kotir, Smith, Brown, Marshall, & Johnstone (2016)	Ghana	Examining the feedback processes and interaction between the population, the water resource, and the agricultural production sub-sectors of the Volta River Basin in West Africa	The objective of the model is to provide a learning tool for policy-makers to improve their understanding of the long-term dynamic behavior of the basin, and as a decision support tool for exploring plausible policy scenarios necessary for sustainable water resource management and agricultural development.	The model demonstrates how the availability of water resources can affect farmers' yield and thus affect farm income, availability of food and food security.

Guma, Rwashana, & Oyo (2016)	Uganda	This research aims to investigate food security challenges, and evaluate policies and intervention strategies for better livelihood at household level.	Assess household food security challenges and factors associated with food availability, as well as find relationships between influence factors in the system	The model is divided in four sectors: population and land, food consumption, food production, and food sales. It demonstrates the decisions farmers make when facing different situations, such as related to market and land, and how it affects the availability of food within the household.
Amelia, Kopainsky, & Nyanga (2014)	Zambia	To study adoption and diffusion patterns of conservation agriculture, and identify coherent policy options to increase the implementation of conservation agriculture	Explaining the economic and social determinants of conservation agriculture adoption. Analyze the implications over time of plausible interventions to foster implementation of conservation agriculture and thus the preconditions for enhancing of conservation agriculture.	The model demonstrates how conservative agriculture, a practice that can increase yield, is affected by factors such as the farmer's knowledge about the practice, perceive profit and labor requirement, as well as the impact on maize production and thus food security.

The review of the five models allowed to perceive that most of the papers apply a system dynamics approach to address specific issues. Sterman (2000) states that the method of system dynamics perfectly suits this application, facilitating the setting of boundaries for discussion and fulfilling data requirements.

Bala et al. (2014) chose to model the rice sector in Malaysia, which is a complex, dynamic, and multi-faceted system depending not only on available technology but also on economic, political and social factors. Fully understanding this system, that contains economic, social, technological, environmental, and political elements, is only possible through a system dynamics approach.

Bala & Hossain (2010) built a complex model containing sectors that together significantly explain the behavior of the coastal zones of Bangladesh, this model is an excellent tool to assess in an integrated manner the management of the system. Furthermore, the model provides an instrument to evaluate the impact of sustainable development on food security. Kotir et al. (2016) explored the processes and interactions between the population, water resources, and agricultural production, creating a model that has the strength to describe the importance that a single element has in a food security system.

Amelia et al. (2014) designed a model not specifically related to food security, instead, they created a model to explain the adoption and diffusion of an agriculture practice that has been an option for addressing the problem of food insecurity and environmental degradation. The conservation agriculture practice is able to increase yields and be used as an adaptation to climate related changes such as droughts (Mazvimavi, 2011). However, this model needs further development to better explain the relationships between the adoption of conservation agriculture and food security issues.

The four models previous described above do not make a statement of the effects of the issue studied on the per capita daily energy dietary consumption, that is, the studies aim on a regional or country level, making the models less relevant for assessing food security at household or individual levels. However, Guma et al. (2016) created a model that express important relationships between factors within a household, including labor, income, and land, and their influence on the availability. The model is able to explain and address challenges of a common African subsistence farmer, and can be applied to different countries.

Overall, all reviewed papers describe the development of a system dynamics model that captures the interactions and feedbacks between key components related to food security. The models can be used as a learning tool to increase the knowledge of the dynamics of the regions they attempt to study. The system dynamics approach is also able to improve the stakeholders understanding of the dynamics behavior of food security, and support the creation of better policies to improve livelihood.

2.3. Zambia Country Profile

Zambia is a landlocked country in Southern Africa covering a total area of 752612 km² sharing borders with Zimbabwe, Botswana, Namibia to the south, Angola to the west, the Democratic Republic of Congo and Tanzania to the north, and Malawi and Mozambique to the east. The country is carved into 10 administrative provinces, 103 districts, and 1421 wards used for sub-district administration and decision-making (Famine Early Warning Systems Network, 2014). The total population was approximately 16,21 million in 2015, growing at a rate of 3,1% per year (The World Bank, 2015).

With some of the largest copper and cobalt deposits in the world, the national economy is heavily dependent on mining; however, agriculture is the mainstay of livelihoods for a majority of the rural population, who constitute 65% (1 631 000 households) of the population. The sector has significant potential for growth with over 50% of the total 39 million hectares of land classified as medium-to-high potential for crop production. Less than half of arable land is cultivated due to limited investment in mechanized agriculture (Central Statistical Office, 2012b). Most agricultural production for subsistence uses traditional technology.

Currently, the agricultural sector in Zambia contributes to about 13% of the GDP. The sector also provides employment to over 50% of the population (Zambia Development Agency, 2014). As such, agriculture has continued to receive priority attention by the government through increased budget support aimed at increasing agriculture productivity to ensure food security, income generation, the creation of employment opportunities, and poverty reduction (Zambia Development Agency, 2011).

In Zambia, 92% of farmers cultivate an area less than 5 hectares, and maize is the dominant crop in the farming system (Weber, 2008). Almost all smallholders grow some maize, and nearly all maize (90%) is grown by smallholders (Gray & Kohl, 2016). Other crops grown include cotton, soybean, cowpea, tea, tobacco, groundnut, sweet potato, cassava, and cucurbit (Weber, 2008). Maize, cassava, and sweet potatoes are grown for food security, unlike cotton and tobacco which are grown for income generating purposes (Denison, 2011).

Cultivation is mostly rain-fed, which necessarily leads to substantial fluctuation in production from one year to the next. Any unfavorable weather condition such as long periods of drought decreases the production substantially (Japan Association for International collaboration of Agriculture and Forestry, 2008). In fact, Zambia's maize production for the 2012/13 growing season decreased by 12%

(from 2,8 million to 2,5 million tons (FAO, 2015b)) due to poor weather and a worm infestation (Mfula & Stoddard, 2013).

Livestock rearing provides a source of food and income for households with slightly more than 50% of households owning different types of livestock including cattle, goats, pigs, or chickens. More than 66% of the population is employed in the agriculture, forestry, and fisheries sectors (Central Statistical Office, 2012a). In addition to agriculture, extra common sources of food and income are related to natural resource exploitation including, timber, charcoal production, fishing, honey production, hunting, and mining. However, overall gains in agriculture output are not well correlated with reductions in poverty (Famine Early Warning Systems Network, 2014). According to the World Bank, in 2010 about 60,5% of the total population were living below the national poverty line, with almost 80% of the rural population below the national poverty line (The World Bank, 2015).

2.4. Overview of Zambia Most Important Crops

2.4.1. Maize

Maize production is the predominant agricultural activity in Zambia, generating output to meet national demand of 1,4 million tons per annum. Yields from the small-scale sector are less than 1,4 tons unless fertilizer is applied to raise them to 2,5 tons. Low yields are attributable to recycled seed, late planting, low input levels, inappropriate spacing and tillage practices and low producer prices. Of all the maize planted since 2004, 33% has been abandoned due to droughts, floods, weed competition or lack of labor. Periodic export bans and price manipulation have deterred farmers from increasing production to levels previously achieved. Average into-mill prices have ranged from \$190 to \$270 per ton since 2004 (USAID, 2009).

Table 2 – Zambian maize sector overview

Maize	Unit	2004-05	2005-06	2006-07	2007-08	2008-09
Planted Area	ha	834 980	784 525	872 812	928 224	1 125 849
Yield	mt/ha	1,04	1,82	1,57	1,31	1,68
Actual production	mt	866 187	1 424 439	1 366 158	1 211 566	1 888 773
Sales	mt	349 734	No data	662 470	534 294	820 318
Lusaka price	K/50 Kg	44 444	37 780	47 625	44 544	68 111
Exchange rate	K/US\$	4680	3650	3830	3305	5190
Lusaka price	US\$/mt	189,93	207,01	248,69	269,56	262,47

Source: Central Office Statistics, FEWSNET (Retrieved from: USAID, 2009)

An estimated 50% of the maize produced in Zambia is applied to subsistence consumption and does not enter the market. Emergent farmer retention for home consumption is of a higher proportion than that retained by commercial farmers for labor or stock feed. The consumer price of maize meal is a

highly political issue it behooves any government, particularly when elections are in the offing, to manipulate consumer prices with all the tools at their disposal. Such tools include input price subsidies, marketing strategies and export bans, all of which militate against farmer profitability. Surpluses are unlikely to arise under these circumstances, particularly as exports are not widely competitive given Zambia's high cost structure within the region. Despite the policy of "Maize without borders" which is promoted in the region, there is a price-penalty for producing a surplus, which falls to the farmers (USAID, 2009)

The Zambia Food Reserve Agency (FRA) is a parastatal, established in 1996, whose mission is to ensure national food security and income of farmers by maintaining a sustainable national strategic food reserve. The FRA also acts as a macro-economic stabilizer for food grown in the country, such as maize. The government, through the FRA, has the responsibility to purchase agricultural crops from smallholder farmers who are located in economically disadvantaged areas in the country during land-preparation and planting season (Kong, 2011).

The producer price of maize is largely determined by the purchasing policy of FRA. FRA plays the role of trader, under government instructions, which aims to reduce the cost to the consumer. Since FRA is the major trader, it has a strong influence on the prevailing price due also to the history of price setting when smallholders heeded the price offered by government and considered it to be the operative pan-territorial and pan-seasonal price, thereby curtailing their inclination to negotiate better return (USAID, 2009).

Maize milling falls into two distinct categories: the commercial sector which uses roller mills and more technically advanced equipment that can separate the germ and the bran to provide refined Breakfast Meal, and secondly the hammer mill industry that is informal and widespread through the rural areas and produces unrefined "mugaiwa" from the whole grain, called Roller Meal. Consumer preferences are for refined products, therefore Breakfast Meal is preferred to Roller Meal (USAID, 2009).

2.4.2. Groundnuts

Zambia was a major supplier of confectionary groundnuts to the World market in the 1960s. However, the parastatal marketing company became a costly burden on producers and collapsed, the basic seed became moribund due to lack of a sustained rejuvenating breeding program. Production declined considerably as most commercial farmers ceased to produce and small-scale farmers were not offered the services and rewards associated with successful marketing arrangements. Groundnuts are now produced almost exclusively by small-scale growers, yields are low as a result, and return to labor falls

far short of its potential (USAID, 2009)

Table 3 – Zambian groundnuts sector overview

Groundnuts	Unit	2004-05	2005-06	2006-07	2007-08	2008-09
Planted Area	Ha	116 494	161 962	144 251	147 320	144 000
Yield	Mt/ha	0,60	0,45	0,58	0,37	0,48
Production	Mt	69 696	74 218	84 010	55 215	70 527
Farm gate price	K/50kg		100,000	50 000	60 000	120 000
Farm gate price	US\$/mt		548	261	363	462

Source: Central Statistics Office, FEWSNET (Retrieved from: USAID, 2009)

Groundnuts form a large component of the traditional Zambian diet and are an important nutritional component. It can be consumed raw or processed, both confectionary nuts and peanut butter. However, the low productivity and poor quality product is a challenge to be addressed through a breeding program and extension work by a party with commercial interest in the successful outcome of such efforts (USAID, 2009).

2.4.3. Beans

There are many varieties of beans known by many different names in Zambia according to their appearance or their provenance. Yields of the traditional varieties are low, in the range of 300 to 500 kg per ha, and they are susceptible to disease, but they are grown for their taste and color preference, although varieties are available with disease resistance and yield potential of 2500 kg per ha (USAID, 2009).

Table 4 – Zambian beans sector overview

Beans	Unit	2004-05	2005-06	2006-07	2007-08	2008-09
Planted Area	ha	45 270	50 496	54 532	55 663	59 588
Yield	Mt/ha	0,40	0,46	0,51	0,43	0,75
Production	Mt	18 161	23 098	27 697	24 164	44 463
Lusaka price	K/50kg	339 300	444 200	424 100	489 550	594 150
Lusaka price	US\$/mt	1450	2434	2215	2962	2289

Source: CSO (Retrieved from: USAID, 2009)

2.4.4. Cassava

Zambian Cassava production increased gradually up to 1975 when 200 000 tons were produced annually. There was a slow acceleration to 1991 by which time production had increased to 400 000 tons. Then a surge in production was registered as output increased rapidly to 900 000 tons by 2007, coinciding with a decline in maize production since 1991. Cassava is almost exclusively a smallholder crop serving a subsistence need. In the cassava growing areas 96% of households produce cassava (and 26% of them sell only 6% of total production) and 49% produce maize, whereas in the maize growing areas 95% grow maize and only 3% grow cassava (and 45% of them sell 25% of total cassava production), indicating a strong dependence on maize even where it is less appropriate (USAID, 2009).

Table 5 – Zambian cassava sector overview

Cassava	Unit	2004-05	2005-06	2006-07	2007-08	2008-09
Planted Area	ha	311 684	361 028	362 354	391 844	398 000
Yield	Mt/ha	2,92	2,92	2,92	2,92	2,92
Production	Mt	911 673	1 056 000	1 059 887	1 146 142	1 160 853
Farm gate price	US\$/mt					45
Ndola meal retail price	K/kg bag	3400	1786	1000	2661	6000
Ndola meal retail price	US\$/mt	726	484	261	805	1156

Source: FEWSNET (Retrieved from: USAID, 2009)

The expansion of production is constrained by lack of marketing and logistical considerations. The value/weight ratio of fresh cassava, with its high water content, implies that the transport costs rapidly exceed value. Cassava provides both fresh leaves and tubers for subsistence consumption. Sweet tubers are eaten fresh and all tubers are chipped and dried or pounded, washed and dried as flour. Fresh cassava can be harvested before maize and is therefore an important component of the diet during the “hungry season” of January and February (USAID, 2009).

2.4.5. Cotton

Cotton is an unquestioned success of Zambia’s shift towards a market economy. After liberalization in late 1994, production rose from 20 000 MT to over 100 000 MT by the 1998 harvest. Production fell again to less than 50 000 MT in 2000, but rose steadily through the first half of the decade and hit nearly 200 000 MT in 2005. Producer prices vary around K1000/kg of seed cotton (Tschirley & Kabwe, 2009).

Zambian cotton is also produced almost entirely by small-scale farmers in Zambia, and their mean yields have risen from about 450 kg/ha in 1996 to nearly 700 kg/ha by 2005. However, only about

10% of the farmers produce cotton (Tschirley & Kabwe, 2009). This is due to the high encouragement on maize cultivation, and little support on the cotton sector. FRA and FISP (Farmer Input Support Programme) supports to smallholder farmers have the combined effect of increasing the profitability of maize production and they make maize relatively more appealing compared to other crop options. The hybrid seed varieties provided by FISP are more responsive to fertilizer than cotton and other crop options for *Zambian* smallholders, and it is widely understood that fertilizer is applied to maize. Thus, when a household is faced with their decisions at planting time of what area to devote to maize, if said household expects to receive FISP fertilizer and hybrid seed or expects to be able to sell their maize output to the FRA at the higher price, then, they will most likely plant maize in a larger area than they otherwise would (Goeb, 2011).

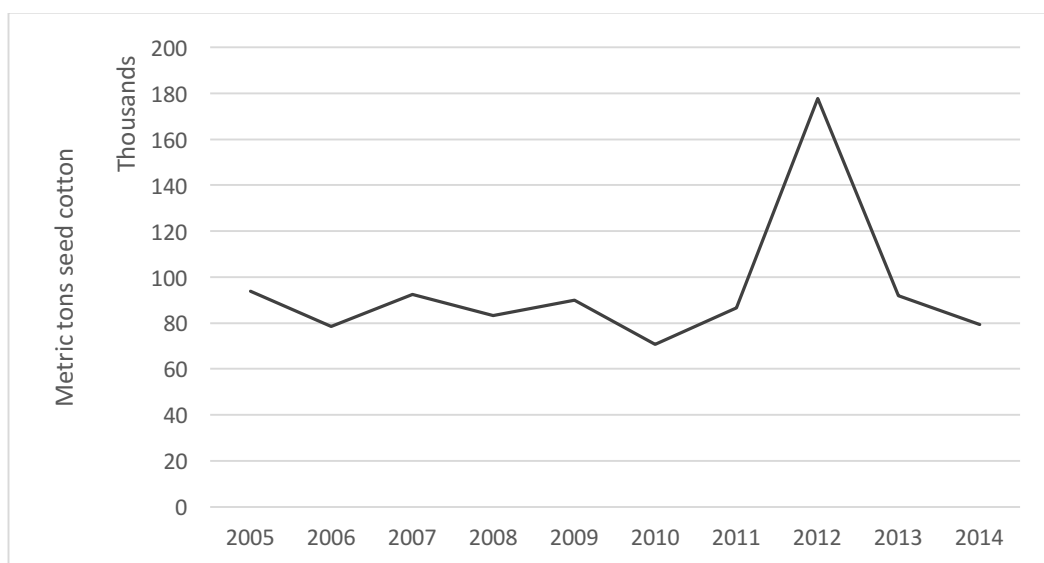


Figure 2 – Cotton production (Source: FAOSTAT, 2014)

2.5. Zambia Fertilizer Sector

The government has implemented a number of policies through various strategic plans to raise agriculture growth. In 1992, the Government of Zambia began to liberalize the agriculture sector from a hitherto state controlled system involving subsidies focused mostly on maize production to increased private sector participation in input and output markets. Notable policy measures undertaken include the liberalization of agricultural marketing for all inputs and products including exports, the privatization of all former agro parastatals and increased private sector participation in commodity marketing and input supply and restructuring of the Ministry of Agriculture and Cooperatives (The Government of Zambia, 2004).

The performance of the agriculture sector has been below expectations in that the growth rate of the sector at 1,5% is less than the population growth rate of 2,8% and the Comprehensive Africa

Agriculture Development Programme target of 6%. Exports mainly consist of primary products and the total value is increasing at a decreasing rate. Poverty and food insecurity are still high among those who depend on agriculture (The Government of Zambia, 2011).

Between 2004 and 2009, the agriculture share (crop, livestock, fisheries and forestry) of the GDP decreased from 15% to 12,5% at an annual average rate of approximately -3,82%. The decrease in agriculture GDP was largely due to the relatively higher growth rates in other sectors of the economy, especially the mining sector. (The Government of Zambia, 2011). Two programs together accounted for over 60% of the public budget to the Ministry of Agriculture over the past years: (i) the “Farmer Input Support Programme” (FISP, formerly known as the Fertilizer Support Programme), which distributes subsidized inputs to farmers, and (ii) the purchase of maize at above-market prices through the Food Reserve Agency (FRA). These programs also accounted for 90-96% of the total budget allocated to the Ministry of Agriculture’s Poverty Reduction Programmes (PRPs) in Zambia during the 2006- 2011 budget years, the FISP and FRA operations have been the main anti-poverty programs in the country (IFDC, 2013).

The FISP was introduced in 2002, following the drought that Zambia experienced. This program was originally designed to address the then declining crop production, especially maize, following successive seasons of droughts and flood that the country had experienced. These calamities had resulted in a diminished asset base for many small-scale farmers, as they attempted to use whatever resources they had to finance crop production, and ensure their own domestic food security. However, over the years the program has evolved resulting in the increase in the number of beneficiaries, the non-graduation of beneficiaries from the scheme and the inclusion of other crops, among other changes (The Government of Zambia, 2015b). An average of 180 000 MT of fertilizer were distributed through FISP each year between 2010/11 and 2012/2013 (Mason, Jayne, & Mofya-Mukuka, 2013).

FISP provides a pack of inputs containing 200 kg of fertilizer and 10 kg of hybrid maize seed (Mason et al., 2013). To be qualified for FISP support a farmer needs to meet different eligibility criteria (The Government of Zambia, 2015b):

- be a member of a registered co-operative society or a farmer organization;
- be a small-scale farmer and actively involved in farming within the cooperative/organization coverage area;
- have the capacity to grow 0,5 hectare of maize;
- have capacity to pay 50% (varies seasonally) of the cost of inputs.
- not concurrently benefitting from the Food Security Pack; and
- not be a defaulter of any agricultural credit program.

These criteria make FISP not succeed in reducing rural poverty in Zambia. The upfront costs, explicit targeting and land access requirements tend to exclude poorer rural households. Farm survey data collected by the Central Statistical Office (CSO) consistently shows that FISP fertilizer and maize seed has been allocated disproportionately to households with relatively large farms and greater asset wealth (Jayne et al., 2011).

Poverty is highly concentrated in farming households cultivating less than two hectares. However, households that cultivating larger areas (and more likely to be above the poverty line) are the ones much more likely to receive FISP fertilizer. For instance, roughly 50% of households that cultivated two hectares and above of land, received FISP fertilizer in 2010–2011 farming season, whereas only 23% and 32% of households in the 0,5–0,99 hectares and 1–1,99 hectare categories received FISP (The Government of Zambia, 2015b).

Government officials are cognizant of the apparent paradox of spending a massive share of the government's poverty reduction budget on relatively large and better off farm households. To redress this, the Government designed the Food Security Pack to explicitly target poorer rural households. However, the budget allocation to the Food Security Packs is just about 5% of the value of the allocation to FISP (Burke, Jayne, & Sitko, 2012).

The Food Security Pack is a 100% grant (as opposed to a loan or cost-sharing program), and targets toward vulnerable but viable farmers that cultivate less than 1 ha and are not in gainful employment. In addition, beneficiary households must be female-, elderly-, or child-headed, keeping orphans or abandoned children, headed by terminally ill individuals, and/or unemployed youth. Food Security Pack beneficiaries all receive 100 kg of fertilizer, 10 kg of hybrid or improved open-pollinated varieties of maize seed, seed to plant 0,125 ha of beans, soybeans, groundnuts, or cowpeas, and 312 cassava cuttings. The Food Security Pack Programme promotes conservation farming practices, with the recommendations tailored by agro-ecological region (Mason et al., 2013).

FISP has clearly contributed to national food production objectives in Zambia. It is estimated that 15% of the increased maize production in 2011 over levels in the mid-2000s was due to increased fertilizer use (Mason, Burke, Shipekesa, & Jayne, 2011). However, the weakness of distribution of fertilizer to poorer households on FISP targeting have severely limited the potential of the program to reduce poverty.

3. Methods

The methodology of the thesis is the base to answer the research questions. It is a tool to elaborate the system dynamics model to assess household level food security, including the valuation of how farm decisions are related to availability of food. The research relies on the case study of smallholder farmers in Zambia. The methodology is divided in different stages: development of a conceptual framework, identification of decisions determinants, model building, scenario analysis, and policy design.

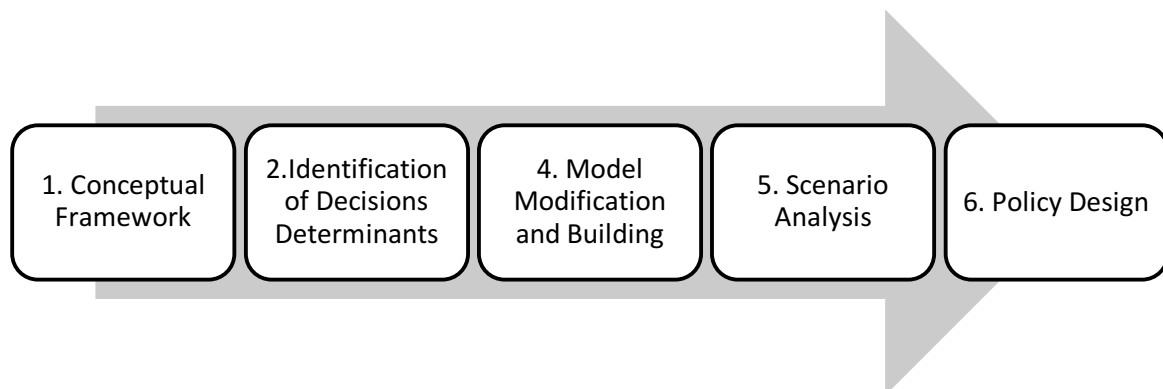


Figure 3 – Stages of the thesis

For the identification of decisions determinants, statistical analyses were performed through IBM® SPSS® Statistics to determine relationships between all the variables documented in the study. Pearson Correlation was used to identify these relationships, and it allowed exploring meaningful factors influencing subsistence farm management. This analysis intends to identify not only factors that influence the farmers crop decision, but as well as relationships between other variables related to farm management. Further analyses were performed using different statistical analysis aiming to quantify and better understand the factors influencing farmers crop decisions. The results of this complementary analysis can be found in the appendix.

Sterman's (2000) methodology for designing a system dynamics model consists of developing a conceptual framework followed by data collection and analysis, and completed with the model building. The first step focuses on the development of a conceptual structure that represents the system's variables and relationships that are responsible of representing a behavior. This structure is formulated based on hypothesis, and the result is the construction of a causal loop diagram (CLD), that summarizes the main relationships and variables regarding a specific theme. This stage is usually made relying on previous researches made in the same field, and insights of experts.

However, as the present study aims, in the first place, to identify the factors affecting farmers crop decisions and farm management relationships, the research followed a different procedure. Preceding

the development of a CLD, it was necessary to determine the relationship between the different options of available crops and several factors through static analysis, only after the conclusion of this stage it was possible to develop a CLD containing causalities previously found in similar researches, and causalities that were unknown and were identified by the statistics analysis.

Gerber (2016) developed a system dynamics model to examine the potential of a fertilizer subsidy program for increasing maize availability in Zambia. The model contains structure related to different elements of the maize production system, including sectors representing the soil dynamics, maize supply and demand, and maize production. Gerber's model was used as a core structure to the model developed in this research. It was further developed to display not only the maize dynamics, but also other crops. Furthermore, it was modified to assess food security at the household level, instead different from the original national-level maize production.

For the scenario analysis, three relevant scenarios were selected to be study, considering the reality of the country and usefulness of the outputs. Three simulations were performed using different initial values for each scenario. A selection of key indicators was chosen to represent the main simulations outputs, which are considered important to assess food security at household level. Finally, the model was simulated with two strategies intending to increase food security.

4. Identification of Decisions Determinants

4.1 About the Data

The data used in this stage of the research was collected by the Conservation Agriculture Project 1 (CAP1). A project executed by the Conservation Farming Unit (CFU) of the Zambian National Farmers Union (ZNFU) from 2006 to 2011. The CFU received funding from the World Bank, EU, and the governments of Canada, Finland, and Norway (Aune, Nyanga, & Johnsen, 2012).

The overall goal of CAP1 was to reverse food insecurity and environmental degradation in Zambia through conservation agriculture. Project activities included promotion of different tillage and ripping methods, introduction of tuber and grain legumes cultivation, guidance on the application of fertilizers and herbicides, and advice on timely planting, and crop rotation. The project also provided machinery, tools, and subsidies. It covered the eastern, southern and central regions, opened to any farmer, reaching over 120 000 farm households (Aune et al., 2012).

The responsible for monitoring the CAP1 was the Department of International Environment and Development Studies (Noragric) of the Norwegian University of Life Sciences. Noragric developed a monitoring system through the establishment of a household survey, field measurements, and on-site visits. The monitoring system included both households associated and non-associated with the project (Aune et al., 2012).

The surveys were annually conducted from 2007 to 2010 and included socio-economic factors, agronomic practices, and labor use. The average of respondents was 525 each year. A follow-up survey with 115 participants was conducted in 2015. The farmers were randomly selected from a list provided by the CFU containing associated and non-associated farmers.

The monitoring effort of the CAP1 resulted in a considerable amount of information that has been only partially studied, and not entirely used for programs and public policies but potentially contain more considerable contribution.

Researchers have analyzed the information for different purposes, for example, farmers' perceptions of climate change (Nyanga, Johnsen, & Aune, 2011), and factors influencing adoption of conservation agriculture (Nyanga, 2012), but there are remaining topics that can be studied, such as identifying the main factors that affect farmers' crop decisions and farming management relationships. This latter tasks are particularly important for designing strategies aimed at accelerating the development of smallholder farms, and programs and policies should be based on an awareness of its relevance and likely impact (Upton, 1987).

4.2. Data Collection Areas

The data used for the identification of relationships was collected in three different Zambian districts, two in the central province (Chibombo and Mumbwa), and one in the eastern province (Chipata). In a total of 11 villages (**Figure 3**).

According to the 2010 census, Chibombo is the largest district in the central province, with a population of 303 519, of which 96% (290115) live in rural areas. Mumbwa is smaller and has 226 171 inhabitants, of which 86% (195131) live in rural areas. Chipata, in the eastern province, has a population of 455 783, and 74% (116627) live in rural areas (Central Statistical Office, 2012b).

All three districts can be classified in the same broad agro-ecological region (Region IIa) (FAO, 2001a). The Region IIa receives about 800-1000 mm of rainfall and has 120-160 days growing season. This region is considered to have the best agricultural potential in the country. The land is suitable for growing a diversified base of primarily rain-fed food and cash crops, and livestock production (Famine Early Warning Systems Network, 2014).

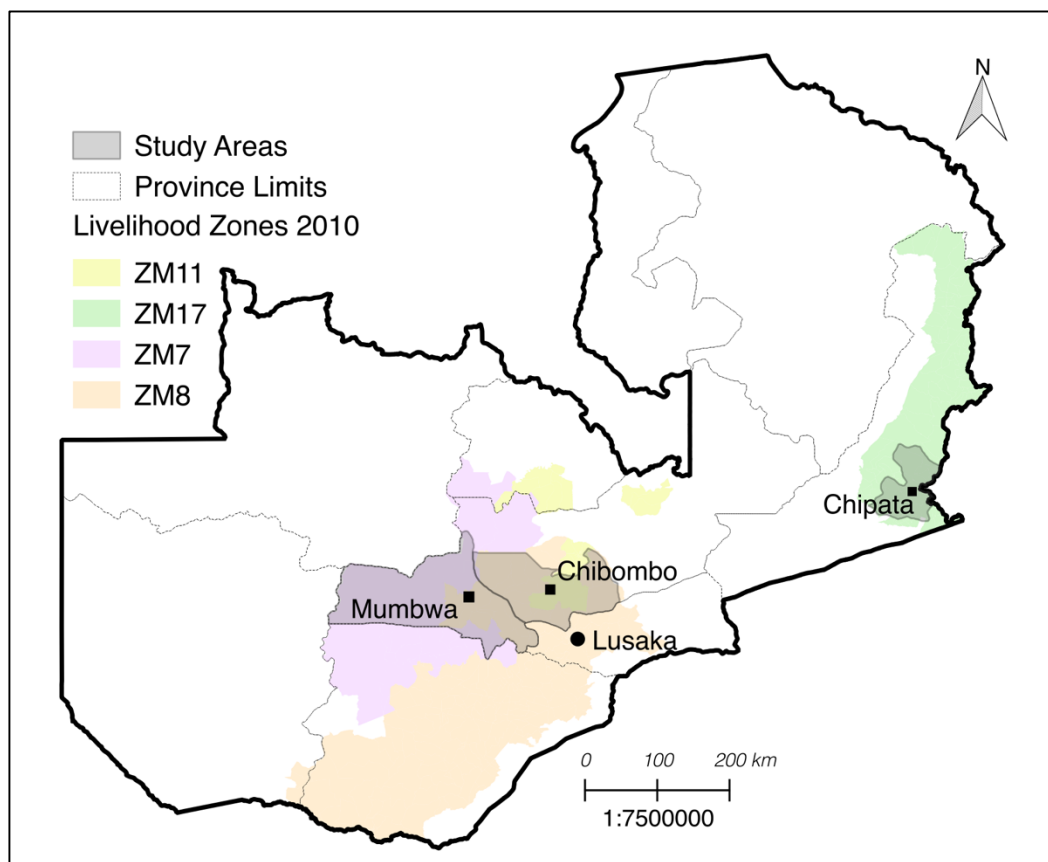


Figure 4- Study areas and livelihood zones

However, the three districts are classified in different livelihood zones (Famine Early Warning Systems Network, 2014):

Chibombo lies most in Zone 8, a densely-populated zone that can count on a rail line and well-developed road linkage to Lusaka. The production of charcoal is relevant. Agriculture is mostly rainfed, but there are irrigated farms. The amount of land cultivated, and productive assets are key factors to determinate wealth groups. The good physical infrastructure facilitates access to trade. However, this zone experiences significant climatic shocks every two-to-three years.

Mumbwa lies most in Zone 7, consisting of smallholders agropastoralists, involving activities such as cattle rearing, crop production, and fishing along the Kafue River. Households grow a wide variety of crops. Tourism is an important characteristic. Livestock type and quantity are key factors to determinate wealth level. Urban centers are well linked to Lusaka, the primary market for this zone.

Chipata falls within the Zone 17, predominantly based on crop and livestock production. Agriculture is mainly rain-fed, with animals used for draft power. Mechanized agriculture is insignificant in this zone. Land and livestock are the primary wealth determinants. Market access is good due to a decent road network, facilitating movement of goods. Trade with Malawi is common in this zone.

4.3. Descriptive Statistics

This stage consists in the statistical data analysis to identify relationships to build a conceptual model. The data was screened for missing values and anomalies. A few outliers were disregarded in different variables due to unrealistic values compared to the rest of the data. Tests were performed excluding missing values in pairwise, and thus the number of cases varies according to the variables in use. The majority of the tests contains a minimum of 90 cases for each variable.

The data contains information about 11 crops of growing season 2014-2015, including the amount of land destined for each crop (**Figure 5**), total production for sale, and total production for household consumption. The criteria used to distinct the crops into three different groups was the main cultivation purpose, whether the household consumes most of the production or sells it in the market. Group 1 is formed by maize, sunflower, and soybeans. These crops take a substantial share of the production for sale purposes and are less retained for home consumption than the second group (Lubungu, Burke, & Sitko, 2013). Group 2 is formed by starchy roots and grains (except soya beans). These crops are mostly grown for home consumption, leaving limited amount for the market (Haggblade & Nyambe, 2007; Mofya-Mukaka & Shipekesa, 2013). Group 3 is formed by cash crops, such as cotton and tobacco, that are grown essentially for sales purposes.

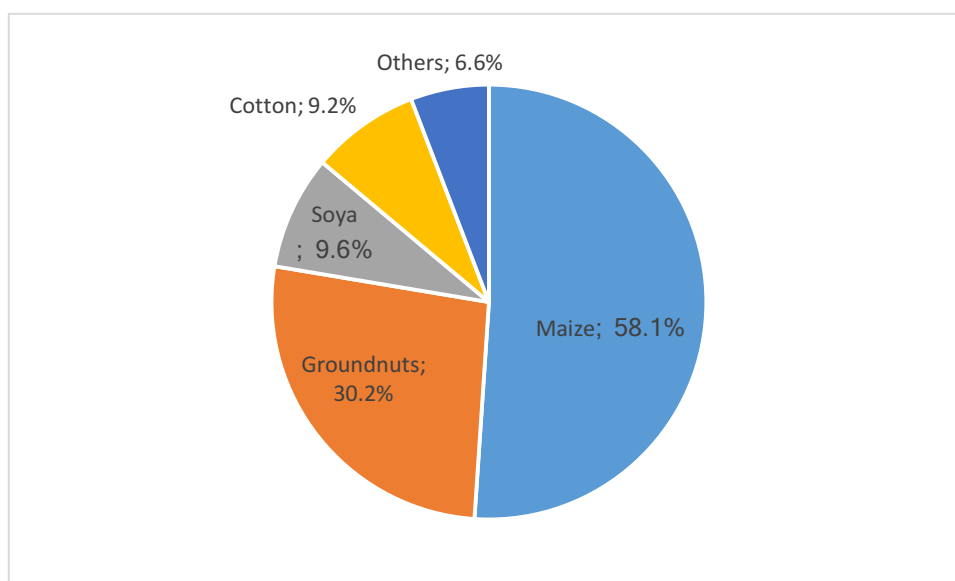


Figure 5 – Share of land allocated for each crop

Table 6 – Groups of crops

Group 1	Group 2	Group 3
Maize	Cassava	Cotton
Sunflower	Sweet potatoes	Tea
Soya beans	Cowpeas	Tobacco
	Groundnuts	
	Mixed beans	

It is important to notice that the agricultural sector in Zambia consists predominantly of subsistence farming and that Group 1 and Group 2 together contain the food crops composing over 75% of the Zambians daily caloric intake. In fact, maize is overwhelmingly the dominant crop, accounting for 40% of the daily caloric consumption (Sitko et al., 2011).

The information relative to the amount of land destined for each crop, and total land was used to calculate the share allocated to each group, creating three main variables of study (**Figure 6**). Values equal to zero (disregarding farmers that did not grow any crop of one group) were excluded to better fit the variables to a normal distribution. This process makes the statistical analysis seek for factors that affect the proportions of land allocated to each group, that is, the factors influencing crop choices.

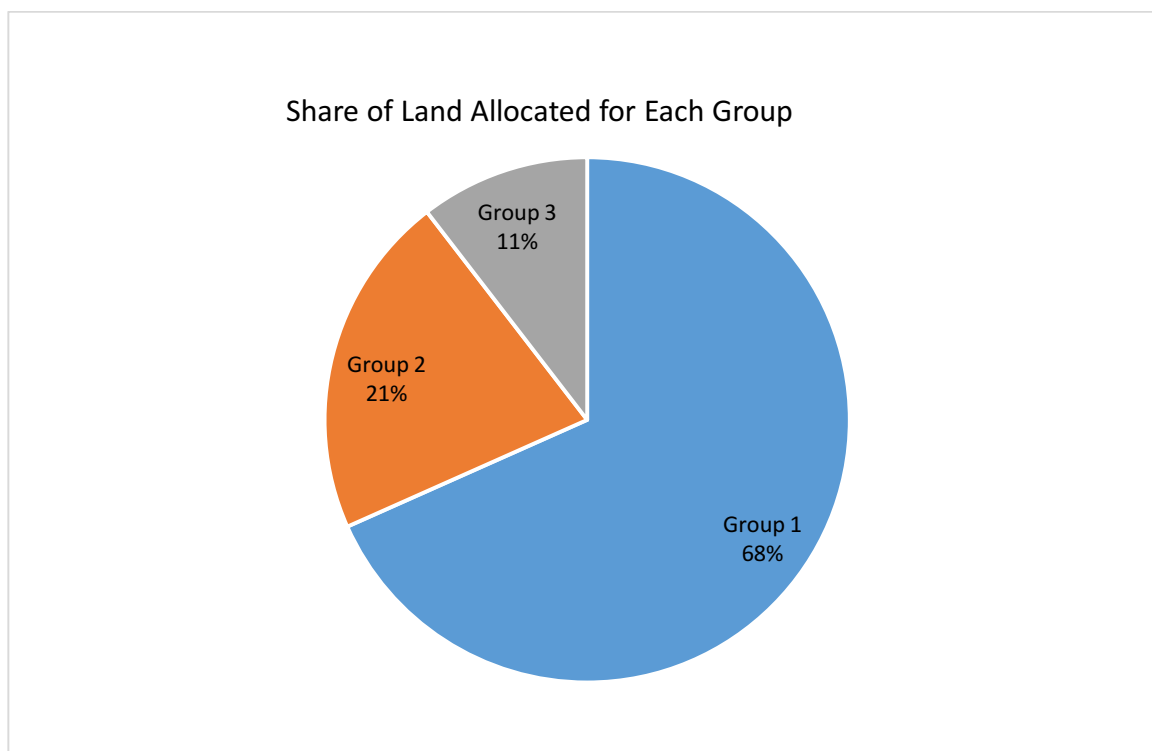


Figure 6 – Share of land allocated for each group

An index was created through multivariate analysis, using listwise deletion, to combine the information of the three main variables into a single one. This process followed the instructions found in Kubrusly (2001), and the specific values are presented in Table 7. The index varies from 0 to one 1. Values move towards 0 when the share of Group 1 rises, and towards 1 when the share of Group 3 rises, facilitating the detection of factors influencing the decisions to plant either cash crops or maize.

Table 7 – Share index description

	Eigenvalue	Score Coefficient	Weight (Eigenvalue ÷ Score coefficient)
Group 1		-1	-0,725
Group 2	1,903	0,587	0,426
Group 3		0,748	0,542

$$\text{Index Value} = \text{Group 1 share} \times -0,725 + \text{Group 2 share} \times 0,426 + \text{Group 3 share} \times 0,542$$

The average total planted area is 3,14 hectares. Group 1 holds the highest share of planted crops, with an average of 65%. Table 2 contains more detailed information on descriptive statistics of variables.

While the surveys were not specifically designed to evaluate farmers' crop decisions, i.e. there are no questions to inquire reasons for choosing a crop, the data collected permits to statistically assess influencing factors. The goal of this stage was to identify broad influences in crop decision and farm management relationships. However, recognizing detailed factors will be imperative for future research.

The data contains essentially socio-economic, and agriculture-related variables. It also includes limited information about farmers' perceptions related to the environment.

Given that decision-making is a wide-range and dynamic process with social and individual components, data for independent variables was compiled on household wealth and size, age and years of schooling of the household's head, and other relevant socio-economic factors. Agricultural-related variables include total planted area and labor force.

Table 8 – Continue variables descriptive statistics

Variable	Unit	N	Mean	Std. Deviation	Minimum	Maximum
Age households head	Year	114	48,82	13,28	22	87
Education Households' head	Year	114	6,93	3,10	0	15
Females Members	Person	108	3,70	1,78	0	8
Group 1 Share	Dmnl	111	0,66	0,20	0,25	1
Group 2 Share	Dmnl	111	0,24	0,15	0,01	0,6
Group 3 Share	Dmnl	111	0,10	0,15	0	0,5
Hired Labor	Person	108	3,23	3,91	0	13
Household Labor	Person	111	4,50	2,17	0	10
Household Size	Person	108	7,14	3,06	1	15
Labor per hectare	Person/ha	92	5,13	3,65	0,8	16
Males Members	Person	112	3,58	2,15	0	9
Members Above 15	Person	107	3,81	1,76	1	8
Members Below 15	Person	113	3,39	2,13	0	9
Share Index	Dmnl	41	0,44	0,20	0	0,85
Share of Fertilizer Subsidied	Dmnl	52	0,64	0,35	0,06	1
Total Labor Force	Person	108	7,96	4,48	1	19
Farm Land Size	ha	108	3,14	2,26	0,13	9,27
Months of Food Inadequacy	Month	36	2,61	1,50	1	6
Fertilizer per Hectare	Kg/ha	96	131,60	8,79	0	307,69

Table 9 – Categorical variables descriptive statistics

Variable	Group	Frequency	%
Lack of Food	Yes	39	33,9
	No	75	66,1
District	Mumbwa	44	38,3
	Chipata	32	27,8
	Chibombo	38	33
Gender of household's head	Male	82	71,3
	Female	32	27,8
Increased Field	Yes	74	64,9
	No	40	35,1
Reasons to Increase Field	To Increase Food Supply	22	30,1
	To Increase Production	15	20,5
	To Access a Better Soil	8	11
	To Have Access to more Inputs	10	13,7
	To Plant a New Crop	13	17,8
	Other Reasons	5	6,8
Abandon Fields	Yes	24	21,1
	No	90	78,9
Reasons to Abandon	Reduced Labor Capacity	6	37,3
	Poor Soil Fertility	13	59,1
	Other Reasons	3	13,6
Perceived Soil Fertility	Poor	22	19,1
	Neither Good or Poor	41	35,7
	Good	40	34,8
	Very Good	11	9,6
Planted Cash Crop	Yes	66	57,4
	No	49	42,6
Rotation Practice	Did Not Practiced	11	9,6
	Practiced	103	89,6
Wealth Level	Low	32	27,8
	Below Average	19	16,5
	Medium	32	27,8
	Above Average	31	27

The descriptive statistics presented in Table 9 illustrates the livelihood conditions of rural households of the three Zambian Districts in study. In terms of households' head gender, 71% are headed by men, and 29% by women. This finding is also similar to that in existing literature (77% male headed and 23% female headed). The found average household size (7,14 persons) is higher than the one found in the literature (5,2 persons) (Central Statistical Office, 2012b). The households' average of years of schooling (6,93 years) is similar to that found by the United Nations (6,5 years) (UNDP, 2012). The share of households stating lack of food (34%) is higher than the share found by the Central Statistical Office (2012b), which is 23,1% for rural areas.

The average total planted area (3,14 ha) is similar to that found in the literature (3,37 ha). However, a quarter of the rural population controls on average barely 1 hectare of land (Sitko et al., 2011). The share allocated for each group is comparable to previous findings. Table 10 compares the values found in this study to previous estimative. The values were adapted from a set of data of area cultivated of each group, and aggregated to form the different groups.

Table 10 – Comparison of results with previous literature estimates

Descriptive Statistics	Crop Forecast Survey, MAL and CSO 2000-2011 (Sitko et al., 2011) - Adapted	
Group 1 Share	66%	54,3%
Group 2 Share	24%	30,7%
Group 3 Share	10%	13,7%

The share of households growing cash crops (Group 3) (66%) is considerable higher than the value found by the Central Statistical Office, which is only 6,56% at the national level (retrieved from Sitko et al. (2011)). This is probably due to that the data was collected in the two provinces where the cultivation of cotton concentrates (Central and Eastern provinces).

4.4. Statistical Analysis Results

4.4.1. Factors Influencing Crop Decisions

Table 11 is a matrix of correlations containing the relationships found in the statistical analysis. Variables that did not present a relationship were disregarded for a better understanding purpose. As it presents, several factors have statistically significant effects on the land shares of the three different groups. Cells marked with green represents relationships that are directly represented latter in the system dynamics model. Cells marked with yellow represents relationships that are indirectly present in the system dynamics model.

With the regard of human capital, variables related to the availability of labor (hired labor force, share of members engaged on farm work, and total labor force) positively affect the Group 1 Share, but negatively affect the Shares of Group 2 and 3. This demonstrates that the available labor force is directed to maize production, the most important crop, which is not only the main source of the households' food, but also income. This finding can also be the answer for the relative low cotton yields in Zambia. Noting that rural smallholder production remains highly labor-intensive. And that, on average, family labor accounts for 62% of the total cost of maize production in Zambia's small and medium-scale farm sector (Burke, Hichaambwa, Banda, & Jayne, 2011).

The size of the household is negative related to the shares of Group 2 and 3. Households with more members tend to allocate less land to crops such as groundnuts and cotton. Instead, larger households seem to dedicate more land to Group 1 crops, as the Share Index is negative related to the size of the household. This relationship may be related to the labor availability, as larger households have more labor force, and tend to direct it to maize production. Furthermore, a larger household demands more food, and securing a stable production of maize is a central decision.

The age of the households' head is negative related to the share of Group 3, meaning that the older farmers tend to avoid planting cash crops. Elderly farmers look at farming as just a way of life, whereas young farmers may be more inclined to look at farming as a business opportunity in order to financially support their families (Sichoongwe, Mapemba, Ng'ong'ola, & Tembo, 2014). In Fact, farms run by young people are, on average, more profitable, and young farmers are more willing to adopt innovative solutions, use environment-friendly farming methods and adjust to market requirements (Vealdi, 2008). Furthermore, planting cash crops can be a risky activity, in case of production loss, it leads to little income, and thus food insecurity. Older farmers may perceive more risk, and decide to not plant cash crops.

For natural capital, the farm land size has a negative effect on the land share of Group 2 and Group 3. No statistical significance relationship was found between the farm land size and the land share of Group 1. However, the farm land size has a negative effect on the Share Index, meaning that it has a positive effect on the Group 1 share. It seems that the farm size has little impact on the tendency to crop diversity. This might be due to the concentration of government support on the production of maize, and little support on the production of other crops, as discussed on Chapter 6,3. However, Kimhi & Chiwele (2000), have found opposite results, that is, the tendency to diversify is positively related to the amount of land.

Variables associated to the availability of food (food adequacy, and months with food deficiency) are related to the share of Group 3. Farmers that allocated a higher share of land to cash crops, were more

likely to report that they did not have enough food for at least one month during the year. The positive relationship between the share of Group 3 and number of months with food inadequacy, indicates that the higher the land share of cash crops, the longer the period with food inadequacy. This outcome will probably influence farmers crop-decision in the following growing season.

The perceived soil fertility is negative related to the share of Group 3, indicating that the better the fertility perception of the field, the lower the share of cash crops. This may be due to that cotton is one of the least extractors of soil nutrients, and thus is usually planted on the least fertile soils, typically with little or no fertilizer (Hake, Cassman, & Ebelhar, 1991). That is, if a farm has fields with poor soil fertility, a farmer will tend to plant more cotton. Furthermore, strengthening this relationship, the total amount of fertilizer is negative related to the share of Group 3.

The district where the farm is situated affects the land share of Group 3. Chipata, in the Eastern Province is the district with higher shares of cash crops. This result is well-known, and is due to the substantial side-marketing and informal trade in the Eastern Province. Chipata is close to Malawi and Mozambique, making the trades of cotton and tobacco more accessible (The World Bank, 2009). In other words, the distance to the market affects the willingness to plant cash crops.

Regarding financial capital, the wealth level has a negative effect on the land share of Group 2. This indicates that the wealthier the household, the lower the groundnuts and cassava production. These better-off households seem to invest more in maize, as the Share Index is negative related to the wealth level. This outcome can be related to the relationship between the gender of the households' head and the Group 2 share. Female headed households are less wealth than male headed households. In fact, female headed households have an annual income 27,5% lower than male headed households (Central Statistical Office, 2012b). Furthermore, maize, the main crop in Group 1, has a higher production cost than the crops in Group 2 (Sitko et al., 2011), and women in Zambia tend to have great control over groundnuts as these are seen as a "women crop" (Nyanga, Johnsen, & Kalinda, 2012). Group 2 crops, when under the management of women, are likely to contribute to household food security and diversify consumption (Mayer, 2015).

4.4.2. Others Important Relationships

Heretofore, it was presented factors influencing crop decisions. However, agricultural systems are complex. It hinges on several elements that affect and interact with each other, and thus creating different outcomes. Therefore, studying these relationships aims to shape and better understand the reality of the farmers. The following paragraphs contain an analysis of secondary relationships that are considered to affect, in an indirect way, the farmers crop-decisions.

The farm land size is one of the most important determinants in developing countries such as Zambia. The statistical analysis displays relationships among several variables and the farm size. Positive relationships were found between farm land size and wealth level, education of the households' head, household size and total labor force. The farm land size is negative related to the gender of the households' head (female headed tend to own smaller amounts of land), and it also influences farmers' decisions to cultivate cash crops (farmers with larger farms are more likely to plant cash crops).

In Zambia, landholding size is strong related to household per capita income, especially for households owning less than 1,25 hectares of land, which applies to roughly 45% of the smallholder population in Zambia. Improving access to land among the most land-constrained smallholder households would be a seemingly effective way to reduce poverty. For small farms, a very small incremental addition to land access is associated with a large relative rise in income (Zulu, Weber, Jayne, & Kajoba, 2009). Although larger farms may produce more, African farmers also face a lack of access to intensifying agricultural inputs (Baltzer & Hansen, 2011), meaning that larger farmers may not produce more due to input constraints, particularly fertilizer, but also credit, and labor.

Another variable related to land is the field increase. Access to land in rural Zambia is largely informal as rights are not recorded and legally enforced (The Government of Zambia, 2015a), due to that, farmers increase their farm land size where possible through deforestation, creating new plots to cultivate. This practice is common in rural areas, as 65% of the interviewed farmers reported that they had increased their farm land size in the previous year. The reasons to increase the farm land size are various, however, 30% of the farmers alleged that they expanded their land to increase household food supply, and 20% to rise production. Yet, although Zambia has abundant potential arable land, as only 33% of the arable land have been explored (FAO, 2012), farmers may find restrictions to expand their fields where population density is higher an land is already occupied, as well as natural constraints, such as areas where flood is usual.

The practice of increasing farm land size is negative related to the wealth level, meaning that wealthier households have less wiliness to expand their land. However, wealth level is positive related to the farm land size, as better-off households own more land, having less need to increase their plots. In the other hand, farmers may also abandon fields. 21% of the interviewed farmers reported that they abandoned part of their farm due to different reasons, such as reduced labor capacity, and poor soil fertility. The area abandoned is, on average, 8% of the total farm land size.

The period without food adequacy is negative related to the farm land size, the education level of the household's head, and perceived soil fertility. As mentioned before, the farm size is an important determinant on household food security, providing greater production and generating more income.

Education known as an important instrument to raise food security. It improves people's capacity to diversify assets and activities, increase productivity and income, foster resilience and competitiveness, access information on health and sanitation, strengthen participation, all essential elements in ensuring long-term food security (De Muro & Burchi, 2007). Soil fertility is also known as a key element to food security, it affects yield and thus the availability of food. Rectifying land degradation and enhancing productivity through appropriate soil management and conservation plays an important role in achieving household food security and agricultural development (Greenland & Nabhan, 2001).

The amount of fertilizer applied per hectare is positive related to the wealth level, and perceived soil fertility, but negative related to the months of food inadequacy. Wealthier households can afford more fertilizer, which increases yield, and thus farmers perceive a better soil quality. Higher yields, as previously mentioned, affects the availability of food, rising the household food security, shortening periods with food inadequacy. Furthermore, the share of subsidized fertilizer is negative related to the wealth level, the gender of the households' head (women headed households have higher shares of subsidized fertilizer as these households are usually less wealth, and may be eligible to the Food Security Pack – see Chapter 6.2), and fertilizer per hectare.

4.4.3. Selection of Causalities

The results and interpretation of the statistical analysis answered the first two research questions. The following question is related to the assessment of food security: **“What is the structure and main feedback loops that explain the food security phenomenon in subsistence farming?”**. As previously mentioned, a system dynamics approach was chosen to solve these doubts. However, before the construction of a system dynamics model, a dynamic hypothesis and model conceptualization need to be done. This step involves the identification of all variables playing potential role in the creation of the dynamics, and the identification of the major causal effects and feedback loops between these variables (Barlas, 2007).

The very purpose of system dynamics study, understanding and improving the dynamics, requires that the model consist of causal relation, not mere correlations. A causal relation means that an input variable has some causal influence on an output variable. If the cause variable is changed, one expects some degree of change in the effect variable. The term “expects” is important in the definition of “causality” in systemic modeling. However, causality is a very difficult and debatable notion. Yet the notion of causality needed for system dynamics modeling is an operational, practical one: non-controversial cause-effect relations, well established either by direct real-life experience or by scientific evidence in the literature (Barlas, 2007).

Every link in the diagram must represent what is believed to be causal relationships between the variables. A system dynamics model must mimic the structure of the real system well enough that the model behaves the same way the real system would. Behavior includes not only replicating historical experience but also responding to circumstances and policies that are entirely novel. Therefore, system dynamics models must include only relationships believed that captures the underlying causal structure of the system (Sterman, 2000).

There are three types of data needed to develop the structure and decision rules in system dynamics models: numerical, written, and mental data. Numerical data are the familiar time series and cross-sectional records in various databases. Written data include records such as operating procedures, organizational charts, media reports, and any other archival materials. Mental data span all the information in people's mental models, including their impressions, stories they tell, their understanding of the system and how decisions are actually made (Forrester, 1980).

The performed statistics analysis works as a first step to identify relationships. However, the identified decision determinants were only assumed to be causalities after further investigation to find appropriate literature that legitimize the statistical analysis. Relationships that did not have proper literature to endorse potential causalities, were left aside and considered inadequate to be part of the model structure. That is, only relationships that are believed to influence the totality of the system were eligible to the model.

4.5. Answers to Research Questions (1) and (2)

The sections 4.4.2 and 4.4.3 contain detailed description and interpretation of the findings in the statistical analysis. The content in the results section allows to answer the first two research question:

1) What are the factors that influence smallholding farmers crop decision?

The found factors that influence smallholding farmers crop decisions can be divided in three different aspects: human capital, natural capital, and financial capital. Regarding human capital, the availability of labor force, the size of the household, the age of the household's head. For natural capital, farm land size, food availability, perceived soil fertility, and the district. For financial capital, the household's wealth level revealed to influence crop decisions.

2) What are the main relationships involved in subsistence farming?

As previously mention, agricultural systems are complex and hinges several elements that interact with each other. Therefore, the statistical analysis revealed important relationships that are involved in subsistence farming which affects crop decisions and other farming outcomes.

Land is one of the most determinants in subsistence farming. It was found relationships between the farm land size and the household's wealth level, level of education and gender of the household's head, household size, labor force, and crop decisions. Relationships were also found between the practice of increasing farm land size with household wealth level, and farmers reported different reasons to abandon fields, such as poor soil fertility or lack of labor force.

The period of food inadequacy was found to be influenced by education of the household's head, farm land size, and perceived soil fertility. Lastly, the amount of fertilizer applied per hectare is related to the household's wealth level, perceived soil fertility, and period of food inadequacy.

5. Dynamics of Subsistence Farming System: The Zambia Case Study

5.1. The System Dynamics Model

5.1.1. Model Structure

This section will describe the stock and flow model developed for the Zambia case study. The model is structured in sectors, each of them characterizing one of the main dynamics of the system. Each sector contains modules that forms the structure that explains the dynamics. The model is composed by 14 sectors. However, as some sectors contain similar structure, due to the similar dynamics, the description below presents the structure of 6 sectors. Yet the sectors do have different parameter values and estimations. The sectors interact with each other, with variables affecting the totality of the system. **Figure 7** presents an overview of the model, showing the exchange of information between sectors, identified by the arrows. For each sector, the key variables linking it to the rest of the system are identified.

The following chapter describes the main structure of the model, presented as subsectors structures that represents the main variables of each sector. The variables believed to be essential to assess household food security are also identified. However, the pieces presented here are a simplified version of the model structure. For the full structure, details of the equations, and parameters source refer to the Vensim version of the model (file available online at: <https://goo.gl/7HQQWD>).

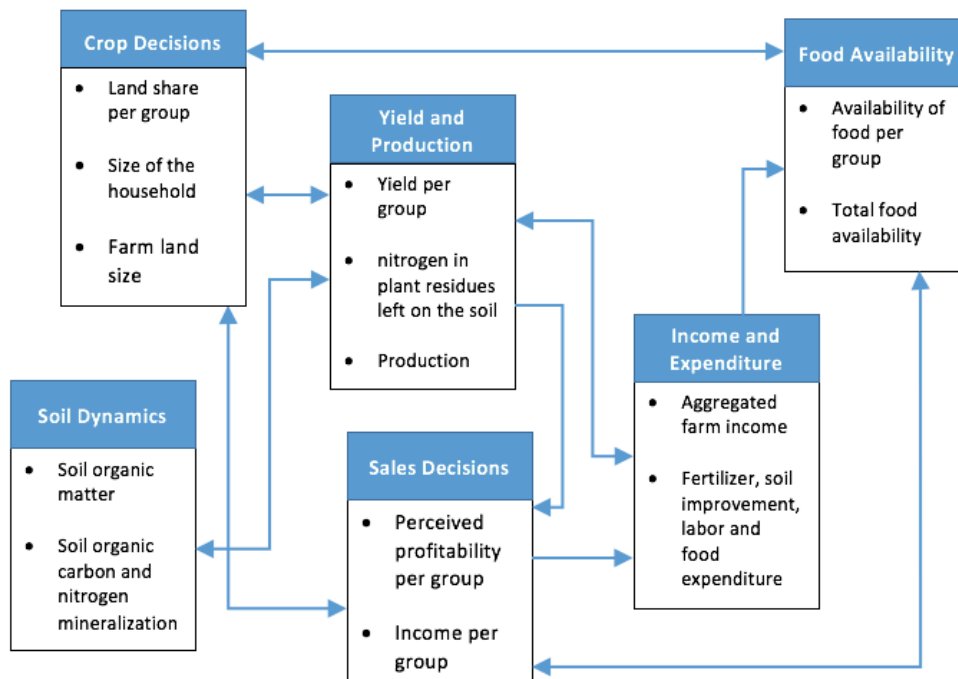


Figure 7 – Model structure overview

5.1.2. Crop Decisions Sector

The crop decisions sector contains the structure that explains the factors affecting farmers’ decisions regarding the three group of crops. This sector contains evidence obtained in the statistical analysis. However, this information was formulated in a way that feedback loops were created, making use of model variables to describe relationships identified in the analysis. For instance, the wealth level was interpreted as the farm income, and the soil fertility is perceived by the yield from the different groups.

Figure 8 presents the factors affecting the decision to plant Group 1 crops: “total labor availability”, “perceived food adequacy from Group 1”, “perceived profit per hectare from Group 1”, and “farm land size”.

The availability of labor is given by the household labor, and hired labor. Household labor depends on the household size, because not all household members are engaged on farm work (i.e. infants, elderly, and members engaged on off-farm work). Hired labor has an average wage, therefore the amount of hired labor depends on the household hiring labor expenditure. Group 1 accounts for over 50% of the Zambians’ daily caloric intake (Sitko et al., 2011), and is represented in the model by the variable “share of Group 1 on diet”. The “perceived food adequacy of Group 1” is the difference between “Group 1 food requirement” and “food availability from Group 1”. Perceiving food adequacy means that the household is approaching the dietary energy requirement. Therefore, food adequacy affects the land allocation depending on how close a household is to meet the minimum dietary energy requirement. The producer price of Group 1 crops affects the perceived profitability, and thus the wiliness to plant these crops. Finally, the farm land size also influences the decisions to plant Group 1 crops. These factors, however, have different weights in farm decisions.

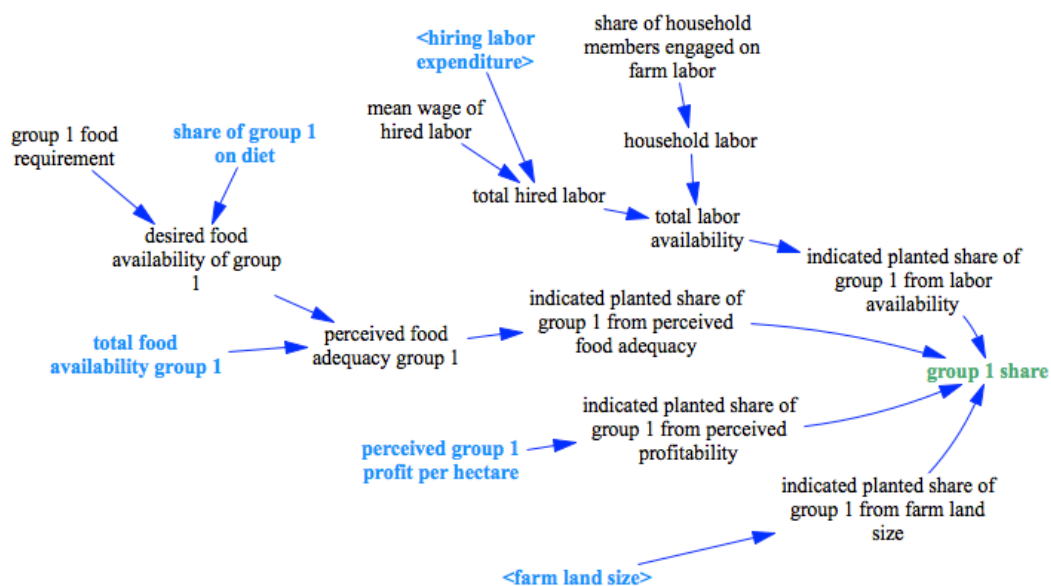


Figure 8 – Summary structure of Group 1 influencing factors

Figure 9 presents the factors affecting the decision to plant Group 2 crops: “gender of the households’ head”, “perceived food adequacy from group 2”, “perceived profit per hectare from Group 2”, “aggregated farm income”, and “Group 1 share”.

Similar to the Group 1 share, the perceived food adequacy influence decisions to grow Group 2 crops. As well as the perceived profitability. The gender of the households’ head affects the decisions to plant Group 2 crops, as previously mentioned, Group 2 contains groundnuts, which are considered to be a “women crop”. The aggregated farm income also reflects on the wiliness to plant Group 2 crops. Finally, the share of land allocated to Group 1 will affect the share of Group 2 and Group 3, assuming that farmers’ decision concerning Group 1 allocation is made first, as maize is the most important crop.

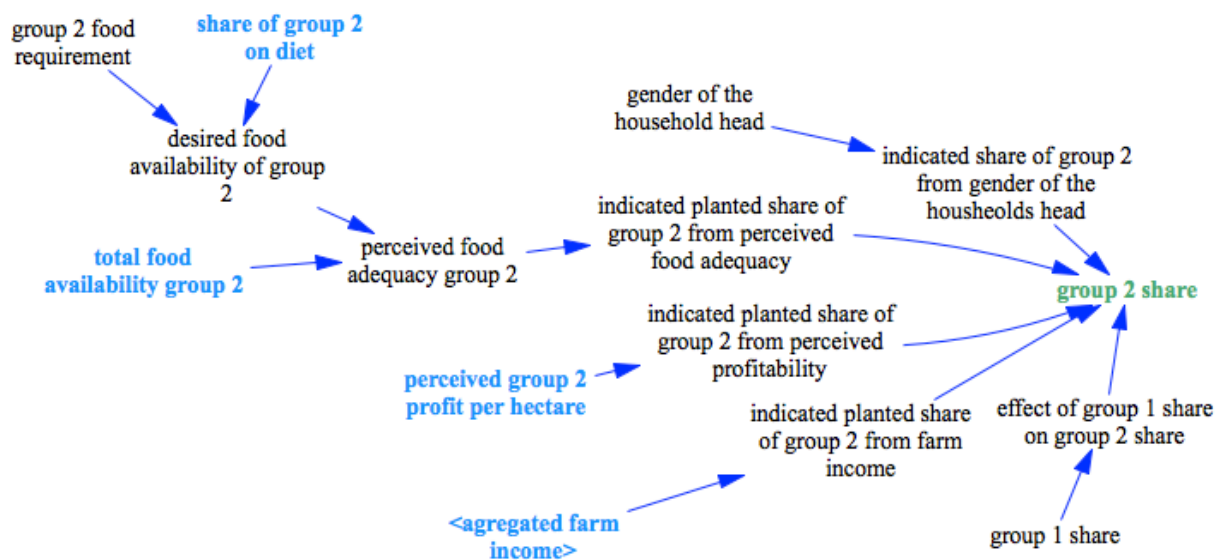


Figure 9 - Summary structure of Group 2 influencing factors

Figure 10 presents the factors affecting the decision to plant group 3 crops: “age of the households’ head”, “distance to market”, “perceived group 3 profit per hectare”, “perceived soil fertility of Group 3 field”, and “Group 1 share”.

Similar to Group 1 and Group 2, the profitability influences the land allocation to Group 3. The age of the household affects the risk perception, and thus influence the decisions to plant cash crops. The district where the farm is located, as previously described, affects the distance to the market, influencing crop decisions. Finally, cotton is usually planted in soils with lower fertility, and soil fertility is perceived through yield, affecting the land allocation to group 3 crops.

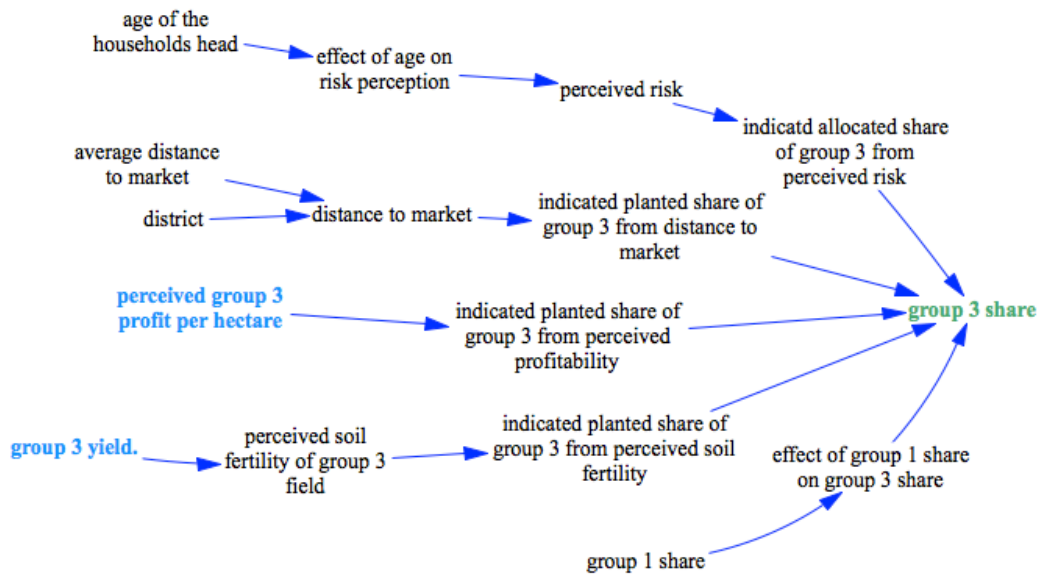


Figure 10 - Summary structure of Group 3 influencing factors

Crop decisions sector also contains the household size and farm land size dynamics. The “household size” is represented by a stock variable, and changes over time by the flows birth and death, according to their crude rate. The “farm land size” dynamics, however, is far more complex, due to the several factors that affect the field increase. These factors were previously identified with the statistical analysis. Farmers reported that they increased their field to rise food supply, and access fields with better soil fertility. Furthermore, wealthier households were less likely to increase their farm land size. These findings were translated into variables able to express the decisions to increase their fields and are represented in **Figure 11**.

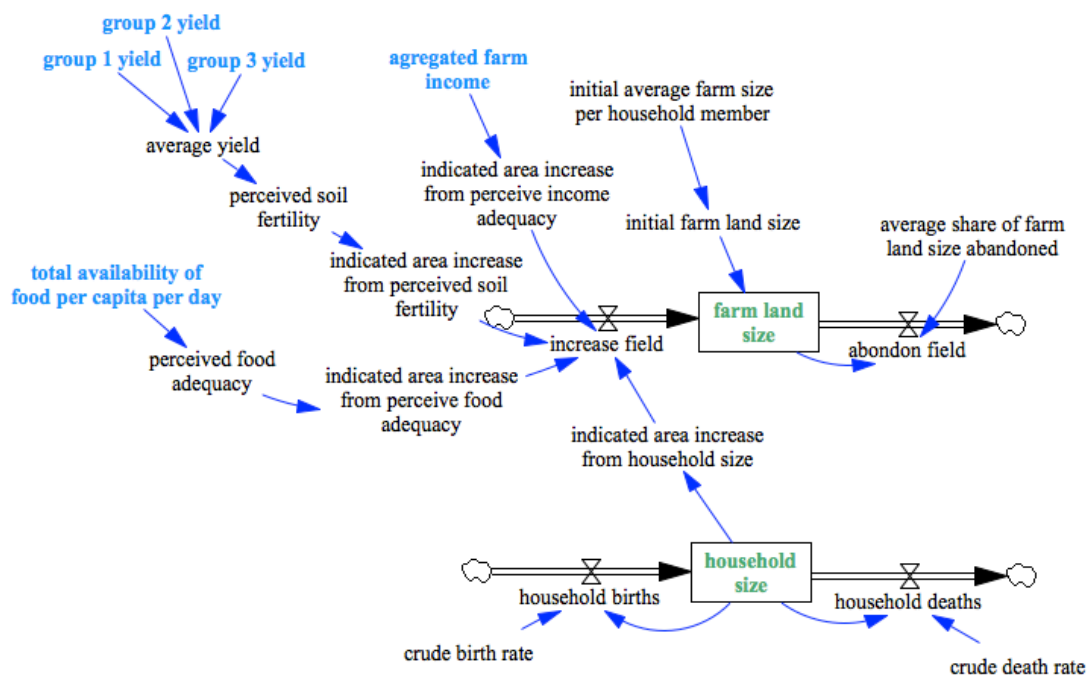


Figure 11 – Household and farm land size structure

5.1.3. Yield and Production Sector

The yield and production sector has two subsectors. The first represents what influences yield (nutrient, and water uptake), and the second subsector represents how yield affect nutrients availability. The variable “(group) yield” represents the amount of crops harvested per hectare (ton/ha). Yield is based on the most crucial limiting factors in Zambia, which are water and nitrogen (Burke, Jayne, & Chapoto, 2010; Shitumbanuma & Chikuta, 2013).

Nitrogen can be obtained through fertilizer application, represented by the variable “fertilizer application per hectare”, and the natural mineralization process, represented by the variable “nitrogen mineralization rate”. Water is exclusively obtained from precipitation, as agriculture is mostly rain-fed (Wani et al., 2009). Soil organic matter affects the availability of water, as it retains water from precipitation, and nitrogen availability. The yield is calculated by a production function based on water and nitrogen uptake. Production is then calculated multiplying yield by the area allocated to the associated Group.

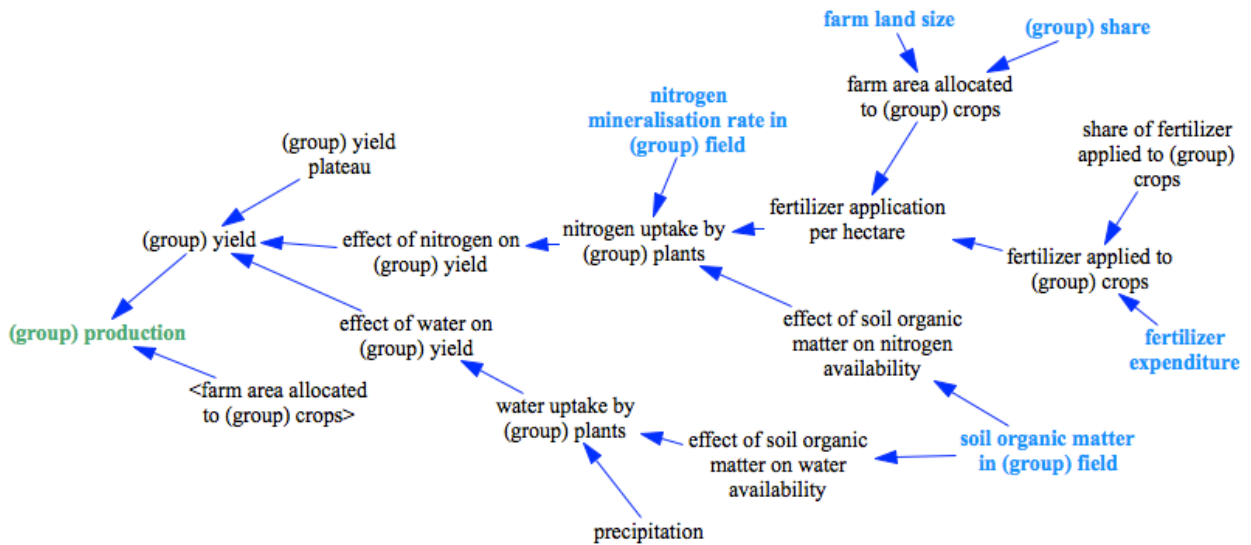


Figure 12 – Yield and production summary structure

After harvesting, farmers leave crop residues in the soil, and the amount left is influenced by yield. Crop residues are left both above and below ground, containing nitrogen that stays in the soil for the next growing season. This helps to improve soil structure, soil water retention, and subsequent crop yields (Haggblade & Tembo, 2003b). However, removing crop residues through burning is a common practice (Verhulsta et al., 2010), as well as for livestock feeding (Muchabi, Lungu, & Mweetwa, 2014). Farmers also expend money on tillage methods, to improve perceive soil fertility, which affects the amount of residues left on the field.

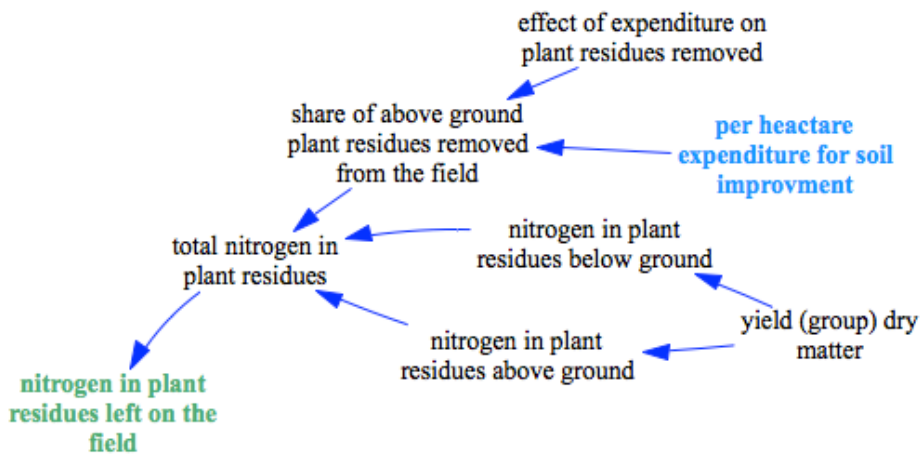


Figure 13 – Crop residues summary structure

5.1.4. Soil Dynamics Sector

Soil dynamics is conceptually split into two elementary components, carbon and nitrogen, according to their different role in the growth process. The plant residues left on the field are converted in soil organic carbon, and thus transformed in SOM, which improves the water holding capacity of the soil, affecting its overall health and improving plant growth (Bot & Benites, 2005). The contained nitrogen in plants residues is converted in soil organic nitrogen, this process is also made by nitrogen fixation through bacteria present in the soil. However, the nitrogen is only available to plants uptake after mineralization, a biological process, which rates vary with soil temperature, moisture and the amount of oxygen in the soil (Johnson, Albrecht, Ketterings, Beckman, & Stockin, 2005).

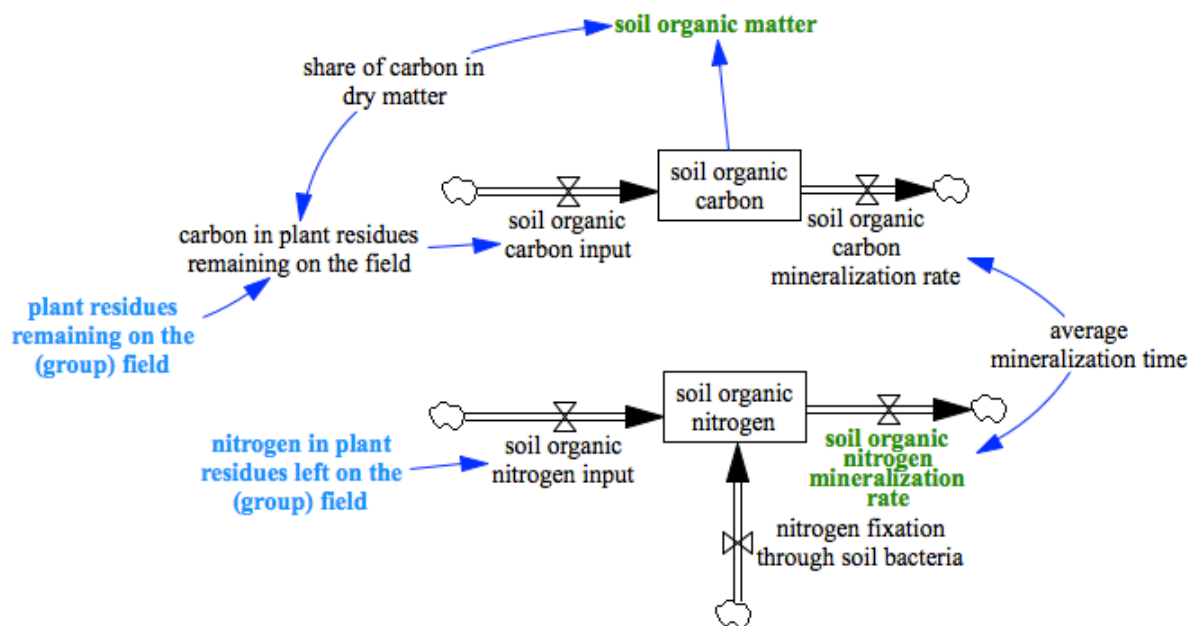


Figure 14 – Soil dynamics sector structure summary

5.1.5. Sales Decisions Sector

In Sub-Saharan Africa, farmers produce food partly for subsistence and part for trading (HLPE, 2013). Farmers weight up the profitability and food adequacy, and subsequently decide to sell a certain portion of the production. This is represented by two variables, the “share of production sold from perceived profitability”, and “share of production sold from food availability”, respectively. Therefore, the income generated by the production depends on the producer prices and the quantities sold. The perceived food adequacy is different for Group 1 and Group 2, due to their different shares on an individuals’ diet. Group 1 accounts for over 50% of the Zambians’ daily caloric intake, and group 2 about 20% (Sitko et al., 2011). The totality of Group 3 production was considered to be sold to the market, as this group is formed by cash crops, cultivated for mainly sales purposes.

The perceived profit per hectare highly depends on the producer prices, that is, the prices that farmers sell their production. For instance, maize producer prices are currently in a negative trend (FAO, 2016), as supply is rising in Zambia. Profit also depends on the farmer expenditure in fertilizer and soil improvement. The more a farmer needs to expend, the less the profit will be. This will affect the farmers’ wiliness to sell the production.

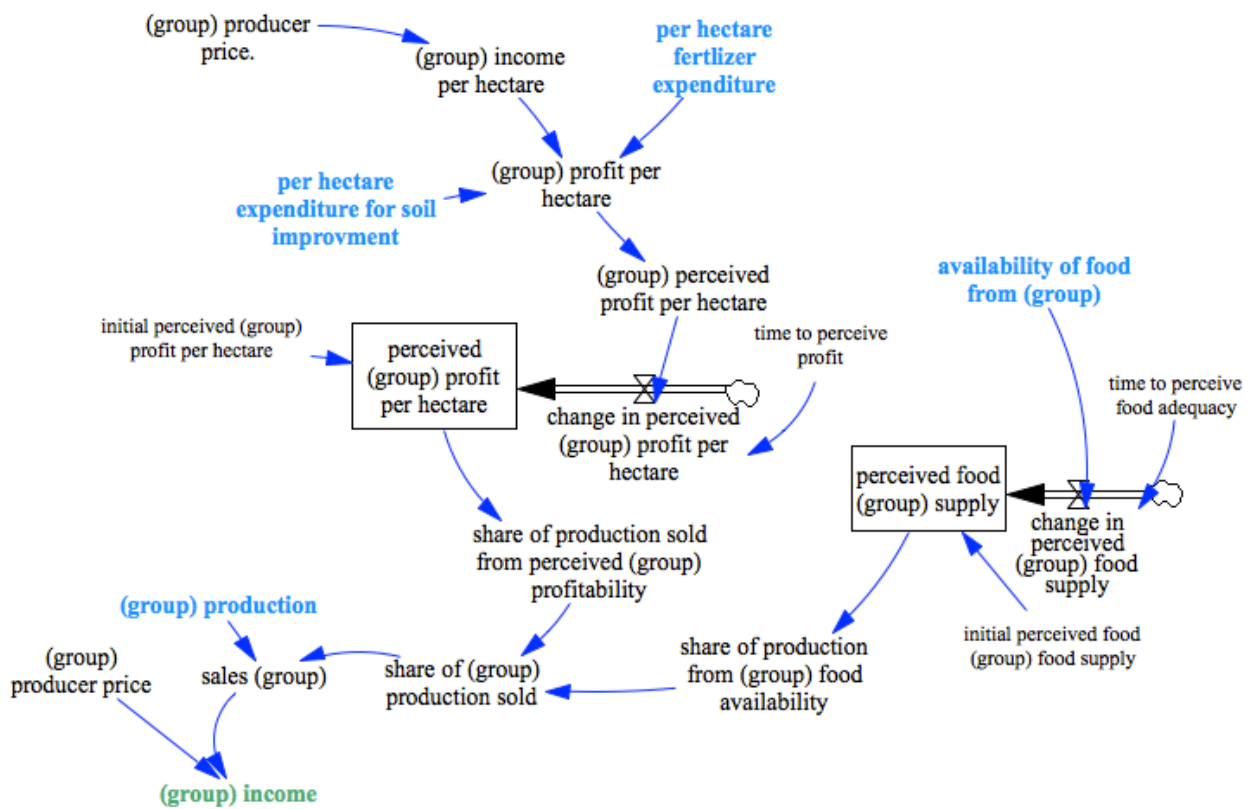


Figure 15 – Sales decisions sector structure summary

5.1.6. Household Income and Expenditure Sector

Household income is generated by the sales of production, and off-farm work by household members, such as selling livestock and handcraft objects in the market, providing more income to the family (Bigsten & Tengstam, 2011). Yet, female headed households usually generate less off-farm income than male headed. The aggregated farm income is spent in different purposes. In rural Zambia, the expenditure in food, consumes over 60% of the total household income (Central Statistical Office, 2012b), and the rest is then expended in other elements. The variable “aggregated farm income” represents the available income generated from the different farm sources. Data for expenditure shares was only available for “share of income to food”, the others expenditure shares were assumed.

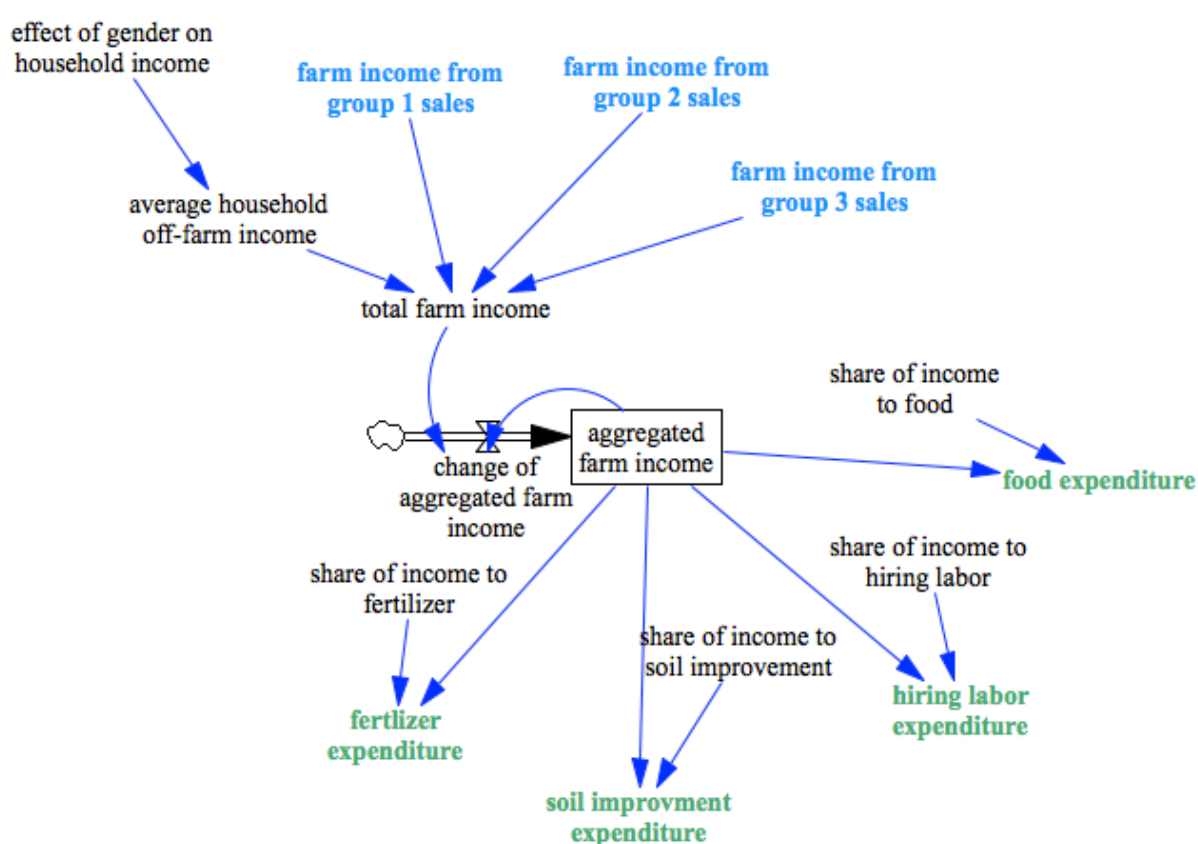


Figure 16 – Household income and expenditure sector structure summary

5.1.7. Food Availability Sector

This sector contains the indicator to assess household food security, which is the total food availability per capita per day in kcal. This indicator includes the availability of food from household production, and purchased food. Although food preferences may change for each household, Group 1 was considered to contribute to 50% to an individuals’ diet, and Group 2, 25%. The variable “for non-food use” represents the part of the production farmers usually retain to recycle seeds for the next growing

season (Smale & Mason, 2012), and animal feeding. As previously mentioned, farmers expend more than half of their income for purchasing food. The variable “total food availability from food baskets in kcal” represents the daily caloric intake derived from food basket purchase. A trend function was created to estimate the average price of the food baskets over time based on data retrieved from the FAOSTAT. The average price for a single basic needs basket for early 2016 was approximately US\$300, but prices may vary according to the district and season (FAOSTAT, 2016)

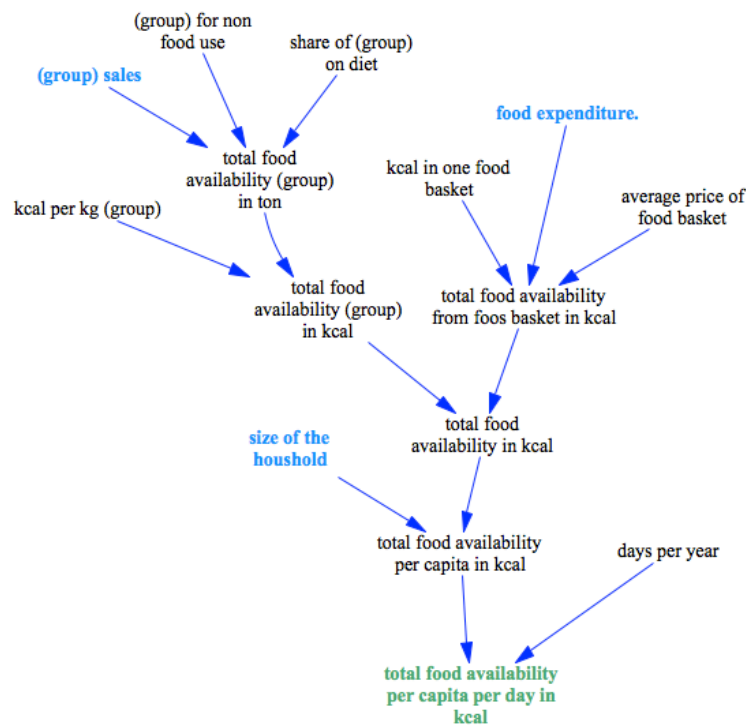


Figure 17 – Food availability sector structure summary

5.2. Indicators

The model structure provides a set of relevant indicators to assess food security in a household level. Table 13 presents the key indicators of each sector that are examined in the scenario analysis.

Table 12 – Models' key indicators

Sector	Indicators
Crop Decisions	Group 1, 2, and 3 shares Farm land size Household size Perceived profit Desired production increase
Yield and Production	Fertilizer applied per hectare Yield Production
Soil Dynamics	Soil organic matter
Sales Decisions	Share of production sold Production sales
Income and Expenditure	Aggregated farm income Fertilizer expenditure Food expenditure
Food Availability	Availability of food per capita per day in kcal Availability of food per group Availability of food from food baskets

5.3. Model Validation

Model validation constitutes an important step in system dynamics methodology. Validation involves quantitative and qualitative tools (Barlas, 1994). There is not a formal and objective procedure to validate system dynamics models (Sterman, 2000). Model validity should be assessed as semiformal process where validity is assessed in terms of its usefulness with respect to a purpose (Barlas, 1996). The intention is to establish that the model is an acceptable description of the real system with respect to the dynamic problem of interest. Model validation is established by two types of tests (Barlas, 2007):

- Structure tests: whether the structure of the model has a meaningful description of the real relations that exist in the problem of interest;
- Behavior test: whether the dynamics patterns generated by the model is close enough to the real dynamics patterns of interest.

As previous explained, the present model uses structures developed by Gerber (2016), and regarding validation Gerber states that “structural validation was achieved through logical, theoretical, empirical, sensitivity, and boundary tests, which were continuously applied throughout the whole modeling process. The model was found to be structurally robust, due to the theory integration, which is the result of extensive structure test procedures. Behavioral validity was achieved through structure-oriented behavior and behavior pattern tests”.

However, Gerber’s model was modified from a national-level to a household-level assessment. Sectors and structures were added to the base model; therefore, validity was altered. Regarding structure validity, the presented model is judged to be satisfying, as the main structure for all sectors (except the “crop decisions” sector, created for the purpose of this thesis) consists of Gerber’s model development, and was nearly all unmodified. Concerning the “crop decisions” sector structure, the statistical analysis, together with appropriate literature endorsement, indicates a consistent structure. Lastly, most of the parameter values correspond directly to available data or empirical literature, and in cases where data was not available, endogenous estimations were made. Regarding behavioral validity, the model was adjusted to reproduce past available data of key variables such as yield and availability of food. The results were found highly similar to the available data, and thus the behavior of the model was judged plausible for the real system.

Nevertheless, the model was developed aiming to demonstrate the entire household system concerning food production and availability. The model presents information from different crops aggregated in three groups. The structure was built to represent averages values for this aggregated information, and thus the results may be biased due to the distinct importance of each crop. Additionally, variations in yield, and sales-related variable are subject to various factors, of which only the main factors are captured in the model. Therefore, the model does not control for all the variations. Instead, it focuses on adequately representing results of empirical indicators trends. Furthermore, the model lacks assessment from policy-makers and specialists to state the actual usefulness to support decision-making, and model validity.

5.4. Causal Loop Diagrams

5.4.1. Subsistence Farming Dynamics

Feedback is one of the core concepts of system dynamics and, to capture the structure of systems, including the critical feedbacks determining the dynamics of a system, diagramming tools are used. A casual loop diagram (CLD) is the most common tool for representing the feedback structure of a system. CLDs are excellent for quickly capturing the dynamics causes, and communicating the important feedbacks responsible for a problem (Sterman, 2000).

All dynamics arise from the interaction of just two types of feedback loops, positive (or reinforcing) and negative (or balancing) loops. Positive loops tend to reinforce or amplify whatever is happening in the system, and are all processes that generate their own growth. In the other hand, negative loops counteract and oppose change. These loops all describe processes that tend to be self-limiting, processes that seek balance and equilibrium (Sterman, 2000).

Figure 18 represents the causal loop diagram for the entire system. However, due to the complexity of the system in study, it was not possible to represent all feedback loops in the same diagram. Instead, the CLD presents the key feedback loops. Yet three CLDs were created to represent the existing feedback loops in the three Groups in study.

The CLD for the entire system contains seven loops that describe the decision dynamics in the household. Feedback loops are displayed in different colors according to the Group they represent. Green is used to represent feedback loops related to Group 1 dynamics, purple for Group 2 dynamics, and blue for Group 3 dynamics. Yellow is used to represent relationships involved in different Groups at the same time, or relationships not directly linked to crop decisions. Reinforcing loops are indicated by the letter “R”, and balancing loops by the letter “B”.

The decision to plant Group 1 crops involves different feedback loops, both reinforcing and balancing. The **“Labor Availability Loop” (R1)** represents the positive effect that labor force has on the land allocation for Group 1 crops. The higher the *Group 1 share*, the larger the *area allocated for Group 1 crops*, increasing *Group 1 production*, and thus *farm income*. The more income, the greater is the *hiring labor expenditure*, hence more labor force is available, positively affecting the *Group 1 share*.

The **“Group 1 Food Supply Loop” (B1)** represents the negative effect of *perceived food Group 1 adequacy* has on *Group 1 share*. The higher the *Group 1 share*, the larger the *area allocated for Group 1 crops*, increasing *Group 1 production*, and thus *total food availability from Group 1*. The more *available food from Group 1*, the greater is the *perceived Group 1 food adequacy*, negatively affecting the *Group 1 share*. That is, the perceived food adequacy equilibrates farmers’ decisions to plant Group 1 crops, meaning that farmers tend to allocate less land to Group 1 crops if they perceive that they have enough Group 1 food. The **“Group 2 Food Supply Loop” (B3)** operates in an equal way for the *Group 2 share*.

The **“Farm Income Loop” (R2)** represents the positive effect that *farm income* has on *Group 2 share*. The higher the *Group 2 share*, the larger the *area allocated for Group 2 crops*, increasing *Group 2 production* and thus the *Group 2 sales*. The more *Group 2 sales*, the greater is the *farm income*, positively affecting the *Group 2 share*.

The **“Profitability Loop” (R3)** is a feedback loop that involves dynamics from Group 1 and Group 3. It represents the positive effect that profitability has on the Group 1 and Group 3 shares. The higher the Group 2 and Group 3 shares, the larger the area allocated for Group 1 and Group 3 crops, increasing *production* and thus the *sales*. The more Group 1 and Group 3 sales, the greater the *farm income*. The more *income*, the higher is the *fertilizer and soil improvement expenditure*, positively affecting *yield*. Higher *yield* leads to a higher *perceived profit per hectare*, depending also on *producer prices* and *fertilizer expenditure*, positively affecting the Group 1 and Group 3 shares.

Farm land size positively affect the *Group 1 share*; however, *farm land size* can change over time, and there are two feedback loops that affect this dynamic. The **“Field Increase Loop 1” (B2)** represents

the negative effect that *total food availability* has on the *farm land size*. The higher the *production* of Group 1 and Group 2 crops, the more *total food availability*, leading to a higher *perceived food adequacy*, negative affecting the *wiliness to increase field*, and thus the *farm land size*. The “**Field Increase Loop 2**” (R4) represents the effect of *perceived soil fertility* has on *farm land size*. The greater the *farm income*, the higher is the *fertilizer and soil improvement expenditure*, leading to higher *yield*. Farmers perceive soil fertility through *yield*, therefore, the higher yield leads to a better *perceived soil fertility*, negative affecting the *wiliness to increase field*, and thus *farm land size*.

The “**Food Expenditure Loop**” (R6) represents the positive effect that *food expenditure* has on *total food availability*. *Farm income* is influenced by crop sales and *off-farm income*. The more *income*, the greater the *food expenditure*. The amount of *purchased food* is negative affected by *food prices*, and positive affected by *food expenditure*. The more *purchased food*, the more *total food availability*.

Lastly, the “**Births Loop**” (R5) and “**Deaths Loop**” (B4) represents the dynamics that affect the *size of the household*. For medium and long term, it is important to demonstrate the increase in household member, as it affects farm decisions, as well as the *availability of food*.

5.4.2. Group 1 Dynamics

Figure 19 presents the CLD representing the dynamics involving Group 1 crops. It contains feedback loops that are not represented in the CLD for the entire system, and excludes the “**Profitability Loop**”, “**Labor Availability Loop**”, and “**Births and Deaths Loops**”. Instead, variables were added to replace these loops. This CLD captures important dynamics related to crop productivity, especially the interaction between fertilizer, yield, and soil dynamics.

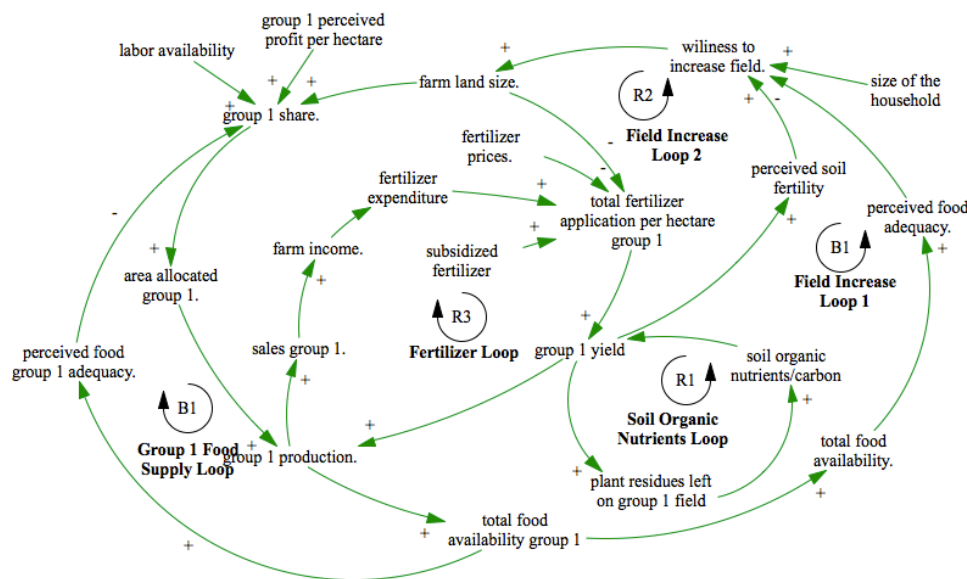


Figure 19 – Causal loop diagram for Group 1 dynamics

Farm land size positively affects the *Group 1 share*, however, *farm land size* can change over time, and there are two feedback loops that affect this dynamic. The “**Field Increase Loop 1**” (B1) represents the negative effect that *total food availability* has on the *farm land size*. The higher the *production* of Group 1 crops, the more *total food availability*, leading to a higher *perceived food adequacy*, negatively affecting the *wiliness to increase field*, and thus the *farm land size*. The “**Field Increase Loop 2**” (R2) represents the effect of *perceived soil fertility* has on *farm land size*. The greater the *farm income*, the higher is the *fertilizer and soil improvement expenditure*, leading to higher *group 1 yield*. Farmers perceive soil fertility through *yield*, therefore, higher *yields* lead to a better *perceived soil fertility*, negatively affecting the *wiliness to increase field*, and thus *farm land size*.

The “**Group 1 Food Supply Loop**” (B1) represents the negative effect of *perceived food Group 1 adequacy* has on *Group 1 share*. The higher the *Group 1 share*, the larger the *area allocated for Group 1 crops*, increasing *Group 1 production*, and thus *total food availability from Group 1*. The more *available food from Group 1*, the greater is the *perceived Group 1 food adequacy*, negatively affecting the *Group 1 share*. That is, the *perceived food adequacy* equilibrates farmers’ decisions to plant Group 1 crops, meaning that farmers tend to allocate less land to Group 1 crops if they perceive that they have enough Group 1 food.

The “**Fertilizer Loop**” R3 represents the positive effect that *total fertilizer application per hectare* has on *yield*. *Fertilizer application per hectare* is negatively influenced by *fertilizer prices* and positively influenced by *fertilizer expenditure* and *subsidized fertilizer*. Expressing that *total fertilizer application* decreases with increasing *fertilizer prices*. Similarly, the *total fertilizer application per hectare* increases (or decreases) with increasing (or decreasing) *fertilizer subsidy* and *fertilizer expenditure*. Higher quantities of *fertilizer applied per hectare* leads to higher *yields*, affecting *group 1 production*, and thus *farm income*. However, this relationship is balanced by *farm land size*. Increasing *farm land size*, may lead to a decrease on *fertilizer application per hectare* if the *fertilizer expenditure* and *subsidized fertilizer* do not increase simultaneously, causing *yield* to decrease over time. Although larger fields may lead to lower *yields*, the *farm land size* positively affect *production*.

The “**Soil Organic Nutrients Loop**” (R1) represents the positive effect that *plant residues left on the field* has on *yield*. Plant residues contain nutrients (nitrogen and carbon) that positively affect *yield*. An increase in *soil organic carbon/nutrients* will lead to higher *yields*. Higher *yields* will leave higher amounts of biomass on the field, which will add more *organic carbon/nutrients* to the soil.

5.4.3. Group 2 Dynamics

Figure 20 presents the CLD representing the dynamics involving Group 2 crops. It contains feedback loops that are not represented in the CLD for the entire system, and excludes the “**Births and Deaths Loops**”. Instead, a variable was added to replace these loops. Similar to the CLD for Group 1 crops, there are feedback loops displaying the interaction between fertilizer, yield and soil dynamics.

The “**Group 2 Profitability Loop**” (R3) is a feedback loop that represents the positive effect that profitability has on the *Group 2 share*. The higher the Group 2 share, the larger the area allocated for Group 2 crops, increasing *production* and thus the *sales*. The more *Group 2 sales*, the greater the *farm income*. The more *income*, the higher is the *fertilizer and soil improvement expenditure*, affecting the *total fertilizer application per hectare in Group 2 field*, leading to higher *yields*. Higher *yield* leads to a higher *perceived profit per hectare*, depending also on *producer prices* and *fertilizer expenditure*, positively affecting the *Group 2 share*.

A feedback loop only present on the Group 2 dynamics is the “**Farm Income Loop**” (B5), representing the negative effect that *farm income* has on the *Group 2 share*. As described in the statistical results, the decision to plant Group 2 crops is influenced by farm income, but such relationship is not found in the Group 1 dynamics. This balancing loop affects the *Group 2 share* negatively. Higher *farm income* leads to lower *Group 2 share*.

The “**Soil Organic Nutrients Loop**” (R1) represents the positive effect that *plant residues left on the field* has on *yield*. Plant residues contain nutrients (nitrogen and carbon) that positively affect *yield*. An increase in *soil organic carbon/nutrients* will lead to higher *yields*. Higher *yields* will leave higher amounts of biomass on the field, which will add more *organic carbon/nutrients* to the soil.

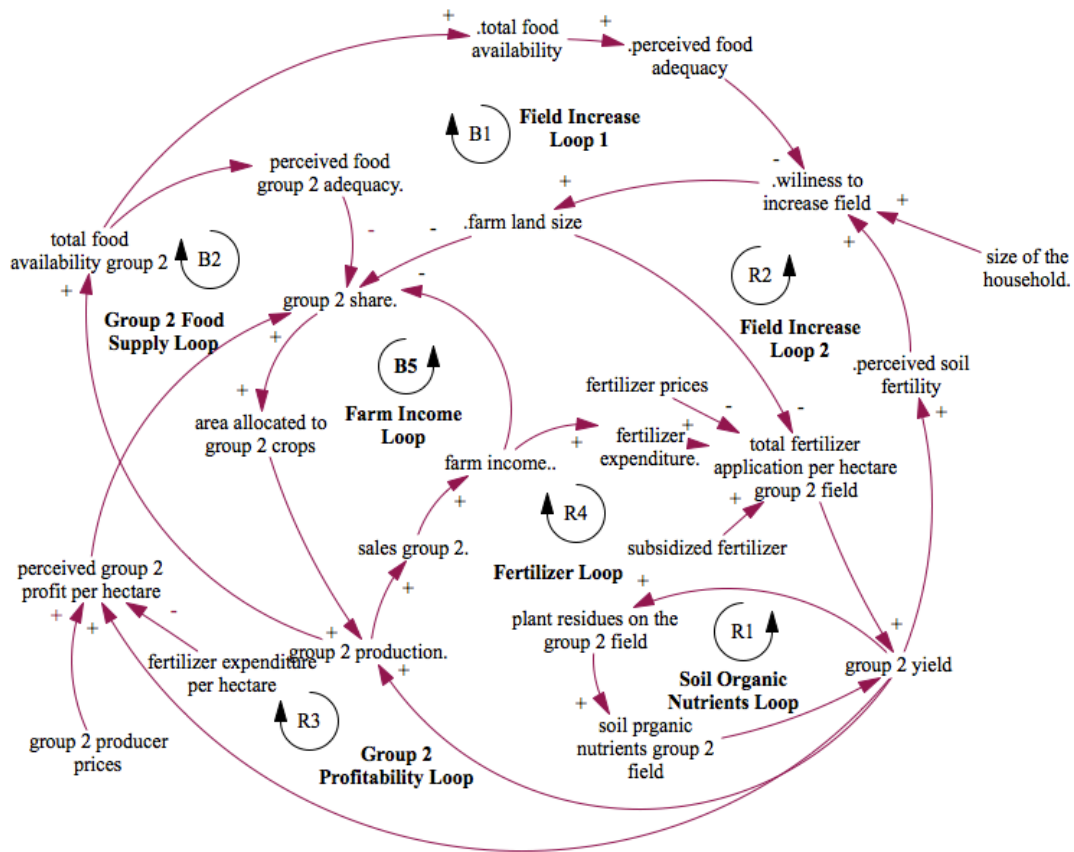


Figure 20 - Causal loop diagram for Group 2 dynamics

The “**Fertilizer Loop**” (R4) represents the positive effect that *total fertilizer application per hectare* has on *group 2 yield*. *Fertilizer application per hectare group 2* is negatively influenced by *fertilizer prices* and positively influenced by *fertilizer expenditure* and *subsidized fertilizer*. Expressing that total fertilizer application decreases with increasing *fertilizer prices*. Similarly, the *total fertilizer application per hectare* increases (or decreases) with increasing (or decreasing) *fertilizer subsidy* and *fertilizer expenditure*. Higher quantities of fertilizer applied per hectare leads to higher *yields*, affecting *group 2 production*, and thus *farm income*. However, this relationship is balanced by *farm land size*. Increasing *farm land size*, may lead to a decrease on fertilizer application per hectare if the *fertilizer expenditure* and *subsidized fertilizer* do not increase simultaneously, causing *yield* to decrease over time. Although larger fields may lead to lower *yields*, the *farm land size* positively affect *production*.

The “**Group 2 Food Supply Loop**” (B1) represents the negative effect of *perceived food Group 2 adequacy* has on *Group 2 share*. The higher the *Group 2 share*, the larger the *area allocated for Group 2 crops*, increasing *Group 2 production*, and thus *total food availability from Group 2*. The more *available food from Group 2*, the greater is the *perceived Group 2 food adequacy*, negatively affecting the *Group 2 share*. That is, the perceived food adequacy equilibrates farmers’ decisions to

plant Group 2 crops, meaning that farmers tend to allocate less land to Group 2 crops if they perceive that they have enough Group 2 food.

Farm land size negative affects the *Group 2 share*; however, *farm land size* can change over time, and there are two feedback loops that affect this dynamic. The “**Field Increase Loop 1**” (B1) represents the negative effect that *total food availability* has on the *farm land size*. The higher the *production* of Group 2 crops, the more *total food availability*, leading to a higher *perceived food adequacy*, negative affecting the *wiliness to increase field*, and thus the *farm land size*. The “**Field Increase Loop 2**” (R2) represents the effect of *perceived soil fertility* has on *farm land size*. The greater the *farm income*, the higher is the *fertilizer and soil improvement expenditure*, leading to higher group 2 yields. Farmers perceive soil fertility through *yield*, therefore, higher *yields* lead to a better *perceived soil fertility*, negative affecting the *wiliness to increase field*, and thus *farm land size*.

5.4.4. Group 3 Dynamics

Figure 21 presents the CLD representing the dynamics involving Group 3 crops. It contains feedback loops that are not represented in the CLD for the entire system, and excludes the “**Births and Deaths Loops**”. Instead, a variable was added to replace these loops. Similar to the CLD for Group 1 and Group 2 crops, there are feedback loops displaying the interaction between fertilizer, yield and soil dynamics.

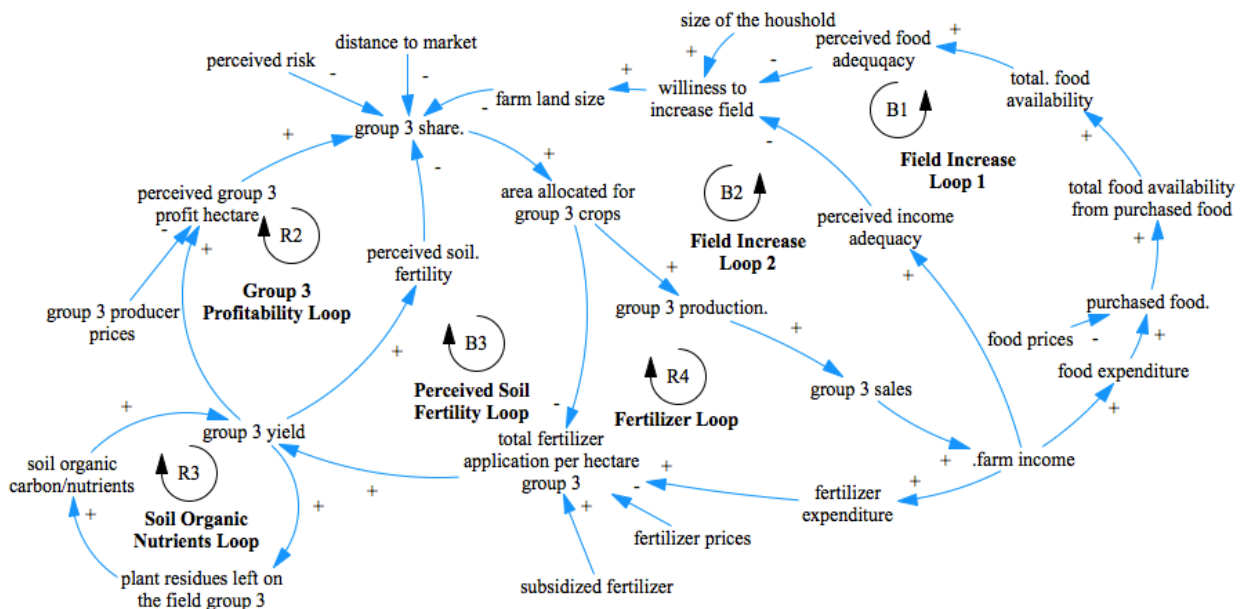


Figure 21 - Causal loop diagram for Group 3 dynamics

The “**Perceived Soil Fertility Loop**” (B3) represents the negative effect that perceived soil fertility has on Group 3 Share. As previously mentioned, Group 3 crops (i.e. cotton) are usually planted on less fertile soil, therefore, the better the *perceived soil fertility* the less land a farmer allocate go Group 3 crops. The larger the *area allocated for Group 3 crops*, the less the *total fertilizer applied per hectare*, leading to lower *group 3 yields*. Farmers perceive soil fertility through yield. The lower the yield, the poorer the *perceived soil fertility*, leading to a higher *Group 3 share*.

The “**Group 3 Profitability Loop**” (R3) represents the positive effect that profitability has on the *Group 3 share*. The higher the Group 3 share, the larger the area allocated for Group 3 crops, increasing *production* and thus the *sales*. The more *Group 3 sales*, the greater the *farm income*. The more *income*, the higher is the *fertilizer and soil improvement expenditure*, affecting the *total fertilizer application per hectare in Group 3 field*, leading to higher *Group 3 yields*. Higher *yields* lead to a higher *perceived profit per hectare*, depending also on *producer prices* and *fertilizer expenditure*, positively affecting the *Group 3 share*.

The “**Fertilizer Loop**” (R4) represents the positive effect that *total fertilizer application per hectare* has on *group 3 yield*. *Fertilizer application per hectare group 3* is negatively influenced by *fertilizer prices* and positively influenced by *fertilizer expenditure* and *subsidized fertilizer*. Expressing that total fertilizer application decreases with increasing *fertilizer prices*. Similarly, the *total fertilizer application per hectare* increases (or decreases) with increasing (or decreasing) *fertilizer subsidy* and *fertilizer expenditure*. Higher quantities of fertilizer applied per hectare leads to higher *yields*, affecting *group 3 production*, and thus *farm income*. However, this relationship is balanced by *farm land size*. Increasing *farm land size*, may lead to a decrease on fertilizer application per hectare if the *fertilizer expenditure* and *subsidized fertilizer* do not increase simultaneously, causing *yield* to decrease over time. Although larger fields may lead to lower *yields*, the *farm land size* positively affect *production*.

Farm land size negative affects the *Group 3 share*; however, *farm land size* can change over time, and there are two feedback loops that affect this dynamic. The “**Field Increase Loop 1**” (B1) represents the negative effect that *total food availability* has on the *farm land size*. The higher the *Group 3 production*, the higher the *farm income*, and thus more *food expenditure*. *Purchased food* is negative influenced by *food prices*, meaning that the higher *food prices* lead to lower *purchased food*. *The more purchased food*, the more *total food availability*, leading to a higher *perceived food adequacy*, negative affecting the *wiliness to increase field*, and thus the *farm land size*. The “**Field Increase Loop 2**” (B2) represents the negative effect of farm income on *wiliness to increase field*. The greater the *farm income*, the higher is the *perceived income adequacy*, leading to a higher *perceived food adequacy*, negative affecting the *wiliness to increase field*, and thus the *farm land size*.

The “**Soil Organic Nutrients Loop**” (R3) represents the positive effect that *plant residues left on the field* has on *yield*. Plant residues contain nutrients (nitrogen and carbon) that positively affect *yield*. An increase in *soil organic carbon/nutrients* will lead to higher *yields*. Higher *yields* will leave higher amounts of biomass on the field, which will add more *organic carbon/nutrients* to the soil.

Group 3 Share is also influenced by *perceived risk*, and *distance to market*. Risk is negative related to the *Group 3 share*. The higher the perceived risk the lower the Group 3 share. The *distance to market* is also negative related to the *Group 3 share*. The further a farm is located from the market, the less area a farmer allocates to Group 3 crops.

5.5. Answer to Research Question (3)

The sections 5.1 to 5.4 contain detailed description and interpretation of the findings in the statistical analysis. The content in the results section allows to answer the first two research question:

3) What is the structure and main feedback loops that explain the food security phenomenon in subsistence farming?

A system dynamics model was chosen to answer this question, and it revealed which factors most influence the food insecurity phenomenon, supporting the understanding of events and causations. The model allowed to analyze the relationship, feedback loops, and behaviors of the substance farming. Furthermore, the model permitted to assess probable scenarios outcomes, displaying critical variables that affect farmers’ decisions and food availability.

The model contains 14 sectors, each of them characterizes one of the main dynamics of the system. Within each sector, different modules form the structure that explains the dynamics. To fully understand the phenomenon, the model represents different areas: Crop decisions, Yield and Production, Income and Expenditure, Soil Dynamics, Sales Decisions, and Food Availability. In that way, it is possible to assess food security looking to real aspects of subsistence farming and understand the constrains and strengths of the entire system.

Regarding the main feedback loops that are present in this system, there are 5 key loops to highlight. **Labor Availability Loop:** the available labor force influences crop decision and sales decisions, affecting the farm income, which affects the hiring labor expenditure, and consequently the labor availability.

Profitability Loop: farm income affects the fertilize expenditure, which increases yield and profitability, influencing crop decisions, hence farm income.

Food Expenditure Loop: food expenditure affects the total food availability, influencing the food adequacy perceived by farmers, affecting the wiliness to increase field, hence farm land size and crop decisions, and thus farm income and food expenditure.

Food Supply Loop: crop decisions affect the area allocated for each crop, which affects the production and thus food availability, and consequently crop decisions.

Field Increase Loop: the wiliness to increase farm land size is affected by the perceived food adequacy and soil fertility, which influenced crop decisions, and thus farm income, and therefore affects food availability and yield.

Farm Income Loop: farm income affects crop decisions, which affects productions and thus sales, and therefore farm income.

5.6. Scenario Analysis

This section presents the model simulation for three different initial conditions: 1) A male-headed household (MHH) initially with 9 members, 2) a female-headed household (FHH) initially with 5 members, and 3) a male-headed household initially with 9 members (9 members MHH). The simulations display how those different conditions affect the farm decisions, and thus the availability of food. The results are presented with different variables of the sectors that reflect on household food security. The results are focused on the variations of the selected variables as key indicators. For a complete visualization of all model variables outputs, refer to the Vensim file (file available online at: <https://goo.gl/7HQQWD>). The simulations are run from year 2015 to 2025, a timeframe that was assumed to express the outcome of farmers' decisions in the present reality of Zambia.

5.6.1. Gender Inequality and Size of the Household

The rural woman plays an essential role in the four pillars related to food security: availability, accessibility, utilization and stability. However, women in rural areas of developing countries are at a disadvantage since they do not have access to the same opportunities or resources as men owing to stereotype issues based on gender. There is a gender gap regarding access to certain resources such as: land, energy, technology, loans, pesticides and fertilizers. Furthermore, women have more limited access to training, information, public services, social protection and markets (García, 2013).

In Zambia, household size, gender, and child status are among the determinants of poverty levels. The incidence of poverty in one-person households was 60%. This rose to 71% in 2-3 person households, 77% in 4-5 person households, 80% in 6-9 person households, and 84% in households with 10 persons or more (Pitamber, 2006).

The majority of small and medium farm households are headed by men while 26% is headed by women (Central Statistical Office, 2012b). If women had the same opportunities in terms of access to productive resources (seeds, fertilizers, tools, loans, etc.) as men, they could increase their yields by 20-30%. This would mean an increase in the production of agro-food of between 2,5% and 4%, thus reducing the number of people affected by malnutrition by around 12-17% (García, 2013).

Due to the differences in types of crops planted by gender, crop management becomes key to distribution of income within rural households. The person who manages a crop has a larger voice in how the resulting income from that crop/ is spent. Households headed by females were less prone to adopting farming cash crops than households headed by males. The decision-making process also varies in issues concerning storage, use of markets and marketing strategies, and use of irrigation technology, depending on crops planted. Furthermore, as a result of male control over production resources, especially land, credit and technology, men take control of the income resulting from sales of agriculture produce, although women continuously contribute in this process (Pitamber, 2006).

Thus, farming decisions have a high level of influence based on gender and these issues will need to be integrated into agriculture programs for successful implementation and uptake of new technologies and crops. In rural Zambia, women's ability to participate in decisions within households is influenced by several factors, such as their education levels, their own income generation capabilities and income contribution to the household, as well as by her age. In this sense, poverty reduction interventions in the agriculture sector must focus on influencing the factors that affect women's equal participation in the decision making process as it ultimately affects access to resources and ability to generate income (Pitamber, 2006).

5.6.2. Crop Decisions Outputs

The Crop Decisions Sector contains variables that represent the factors influencing crop decisions, as well as variables representing the households' growth, and farm land size dynamics.

Figure 22 presents the household growth for the simulation process. The MHH and FHH, initially with 5 members, grows to 8 members in 2030. The third household, initially with 9 members, grows to 14 members in 2030. As the crude birth rate (42,4 births per 1000 people) is higher than the death rate (13,10 deaths per 1000 people) (Central Statistical Office, 2012a), the household size increases over time for all three households.

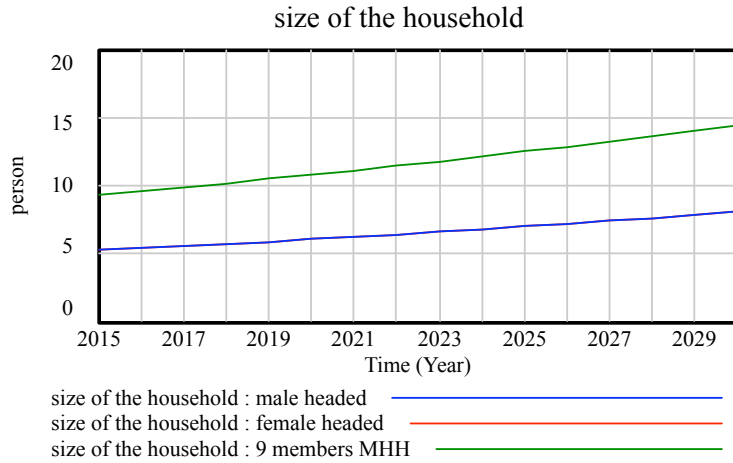


Figure 22 – Model output – Size of the household

A growing household size is one of the causes for an increasing land demand. Farmers will increase their farm land size to supply the household food demand. However, women and men have different access to land. Female head households have more difficulty on acquiring land than male headed households. The farm land size graph displays in 2015 a farm of 1,2 ha if headed by a female, and 1,6 ha if headed by a male. These values grow for both households, and in 2030 reaches 2,4 ha and 3 ha, respectively. A difference of 20% in the farm land size.

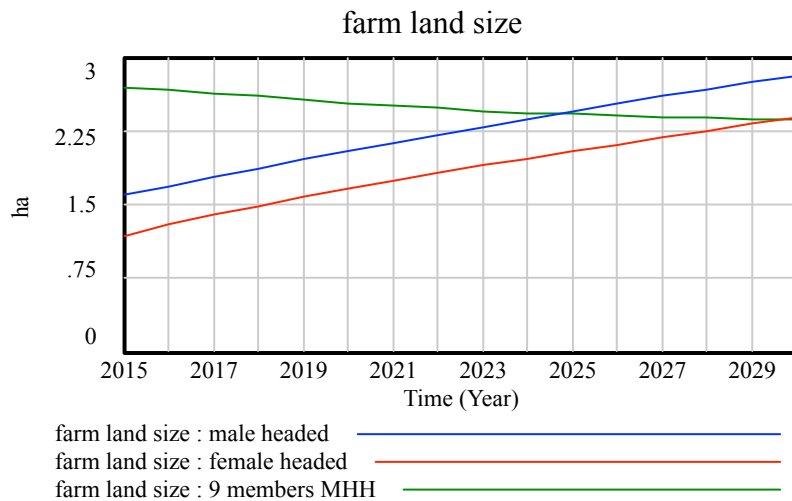


Figure 23 - Model output - Farm land size

The 9 member MHH begins the simulation period with a farm land size of 2,7 ha, as the initial value was calculated based on an average of farm land size per capita. However, for this household, the rate for abandoning fields is higher than the rate for increasing fields, causing the farm land size to decrease over time and reach 2.4 ha in 2030.

Regarding crop choices, FHH and MHH also select differently. The two main factors that influence crop decisions are the perceived food adequacy and perceived profitability. The graph presenting the Group 1 Share, displays that in 2015 FHH allocated 57% of their land to Group 1 crops, against 60% of MHH. These values decrease over time, and in 2024 FHH and MHH allocate the same proportion of land to Group 1 crops (56%), from this point forward, FHH allocated higher shares of land to Group 1 crops than MHH. In 2030, FHH allocate an average 2% higher (56%) than MHH (54%). The household with 9 members allocates a slight higher share to Group 1 crops, initially allocating 62% and decreasing to 55% in 2030.

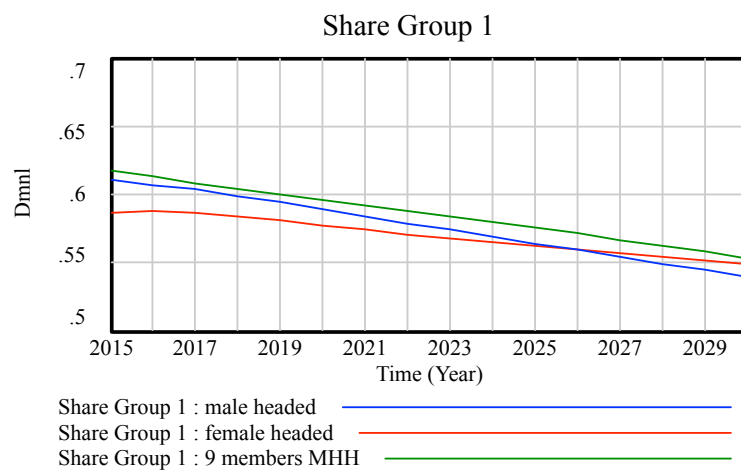


Figure 24 – Model output – Land share of Group 1

Farmers desire to meet the dietary energy requirement of 2056 kcal/person/day (FAO, 2009), and Group 1 accounts for 60% of the energy intake (1233 kcal/person/day). As farmers perceive that they are closer to reach this value, the willingness to plant Group 1 crops decreases. Additionally, perceived profitability also is a major influence on farmers' decisions. The current decreasing Group 1 producer prices due to a higher supply over the past years (FAO, 2016), leads to a decrease on the land share of Group 1 crops.

FHH expends less income on fertilizer and soil improvement, instead they expend more for purchasing food. This leads to FHH perceive a higher profit per hectare than MHH. The perceived profit per hectare for all three households is approximately US\$250 in 2015, for the FHH and MHH it decreases to US\$150 in 2030, a change of 40%, and to US\$100 for the household with 9 members, a change of 60%.

For the FHH and MHH the desire to rise Group 1 food supply decreases over time, as food supply increases. In the other hand, as the household size and food demand increases faster, the household with 9 members desire to increase Group 1 production.

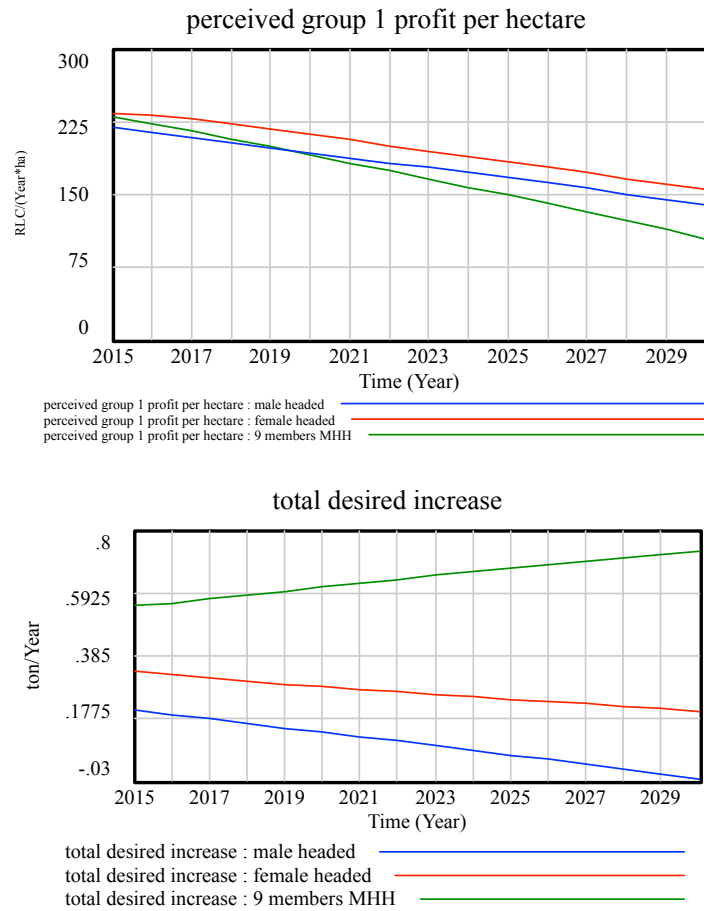


Figure 25 – Model outputs – Group 1 perceived profit and desired production increase

The decision to plant Group 2 crops is also influenced by perceived profitability and perceived food adequacy. However, due to an increasing demand for groundnuts and cassava, producer prices are rising (FAO, 2016), and farmers tend to increase their production of Group 2 crops. FHHs current allocate higher shares of their land to Group 2 crops than MHH (Nyanga et al., 2012). The graph in **Figure 26** shows an increasing land allocation to Group 2 crops. MHH allocate an average of 25% of their land to Group 2 crops in 2015, and increase it to over 35% in 2030. FHH allocate approximately 37% of their land to group 2 crops in 2015, and increase it in a lower rate than MHH, reaching approximately 45% in 2030.

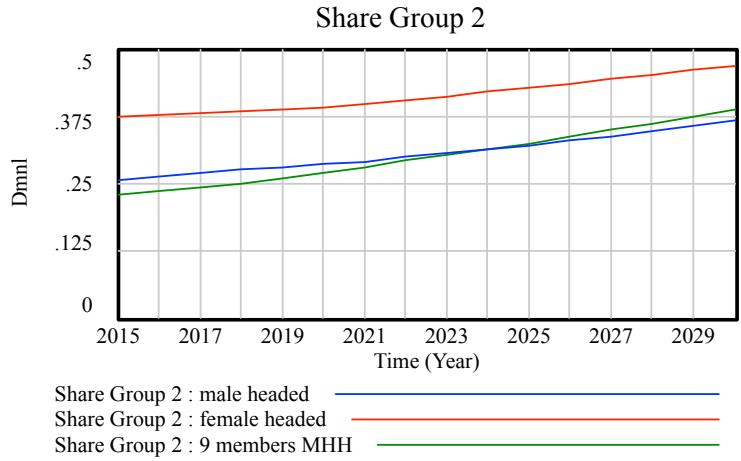


Figure 26 - Model output – Land share of Group 2

The decision to plant Group 3 crops is highly influenced by producer prices, as this group contains only cash crops such as cotton. As producer prices are current rising due to and increasing demand, farmers tend to allocate more land to these crops (FAO, 2016). However, this process is balanced by the perceived risk, which increases as the farmer ages. Furthermore, FHH tend to grow less cash crops, instead, they focus on food crops (Pitamber, 2006). These processes are showed in the graph below, and displays that the FHH did not plant Group 3 crops in 2015, and begins to grow these crops in 2016 in a small share of their land, slightly increasing this value up to 8% in 2016, and maintaining until the of the simulation. MHH allocated 7% of their land to cash crops, increasing up to 15% in 2022, maintaining this value until 2030.

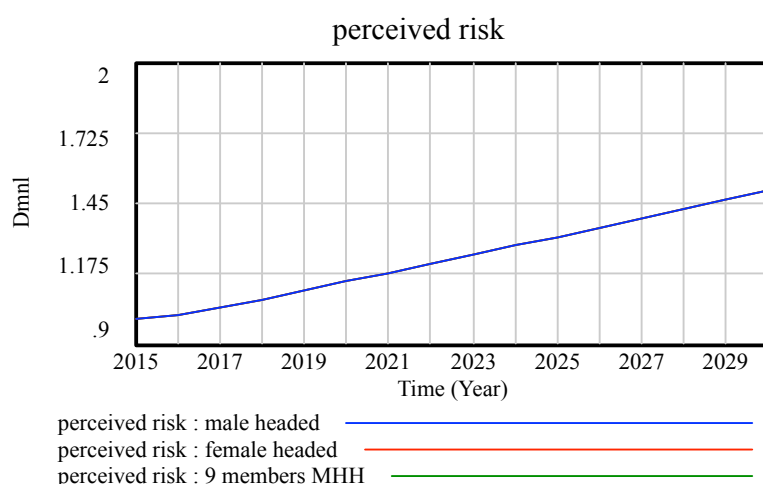
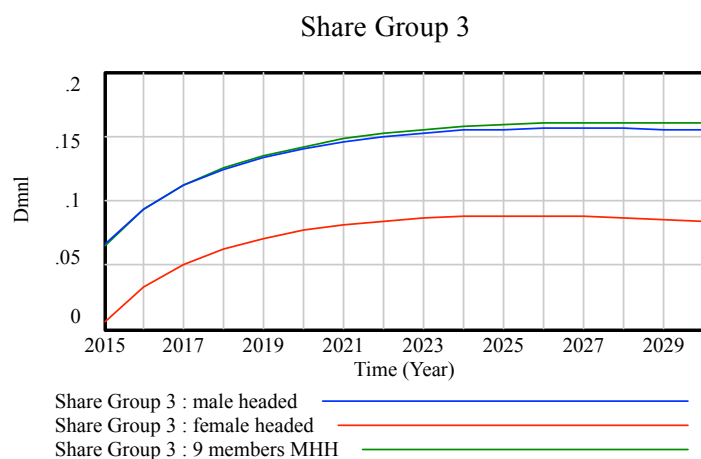


Figure 27 – Model outputs – Land share of Group 3 and perceived risk

5.6.3. Yield and Production Outputs

Fertilizer is one of the limiting factors that affect yield in Zambia (Shitumbanuma & Chikuta, 2013), farmers highly depend on fertilizer subsidies (IFDC, 2013), and FHHs do not have the same access to fertilizer as MHHs, and usually expend less of their income to buy fertilizer from private sources (García, 2013). Furthermore, farmers distributes different shares of their fertilizer to the different crops. Group 1 crops consumes up to 80% of the total available fertilizer, Group 2 crops up to 20%, and for Group 3 crops usually none fertilizer is applied or less than 1% of the total (2005 FAO, 2005).

This translates into different amounts of fertilizer applied by the FHH and the MHH. The **Figure 28** displays that, even though the farm land size for the MHH increases more than the FHH, it still applying more fertilizer per hectare than the FHH. The household headed by a male applied, on average, 120kg/ha of fertilizer to Group 1 crops, slightly increasing it to 135kg/ha in 2030. However, the amount of fertilizer applied per hectare of Group 1 in the FHH decreases from 100kg/ha in 2015 to 80kg/ha in 2030. The household with 9 members significantly increases the fertilizer applied to Group 1 crops due to the fact that the farm land size decreases over time, as well as the share of land

allocated to Group 1 crops.

A different dynamics is observed for Group 2, as the MHH and the FHH increase their land shares for Group 2 crops, the fertilizer application per hectare of Group 2 decreases. In the other hand, also due to the decreasing farm land size, the household with 9 members slightly increase the fertilizer applied per hectare of Group 2 crops. Additionally, it was considered that both households do not apply fertilizer for Group 3 crops.

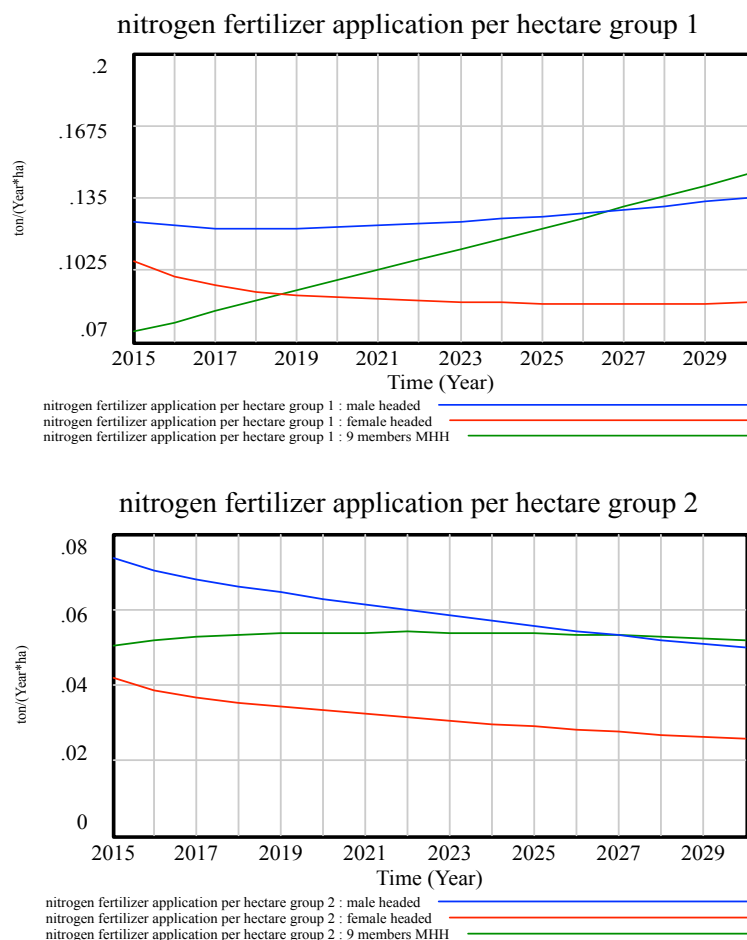


Figure 28 – Model outputs - Fertilizer application per hectare in Group 1 and Group 2 fields

The amount of fertilizer applied highly influences yields and, as previously described, the FHH and the MHH apply different fertilizer quantities to their land, and thus the two households have distinct yields. As MHH apply more fertilizer per hectare, their yields are higher than FMM, and increase over time in a higher rate. For Group 1 crops, the MHH increases the yield from 2,15 ton/ha in 2015 to 3,20 ton/ha in 2030. The FHH have lower yields than the MHH, also increasing over time, from 2 ton/ha in 2015 to 2,4 in 2030. The household with 9 members initially has the lowest yields (1,7 ton/ha), yet is able to increase it to 3,15 ton/ha as the fertilizer application per hectare substantially increases.

Although the amount of fertilizer applied to Group 2 decreases over time in the MHH and the FHH, the crops in this group add nitrogen to the soil through the fixation process, balancing the amount of this nutrient in the soil, and thus the average Group 2 yields, for these two households, remain nearly constant throughout the simulation period. For the FHH the Group 2 yield is approximately 2,1 ton/ha, and for the MHH is 2,6 ton/ha. However, the household with 9 members is able to significantly increase Group 2 yields, from 2,25 ton/ha in 2015 to 2,6 ton/ha in 2030.

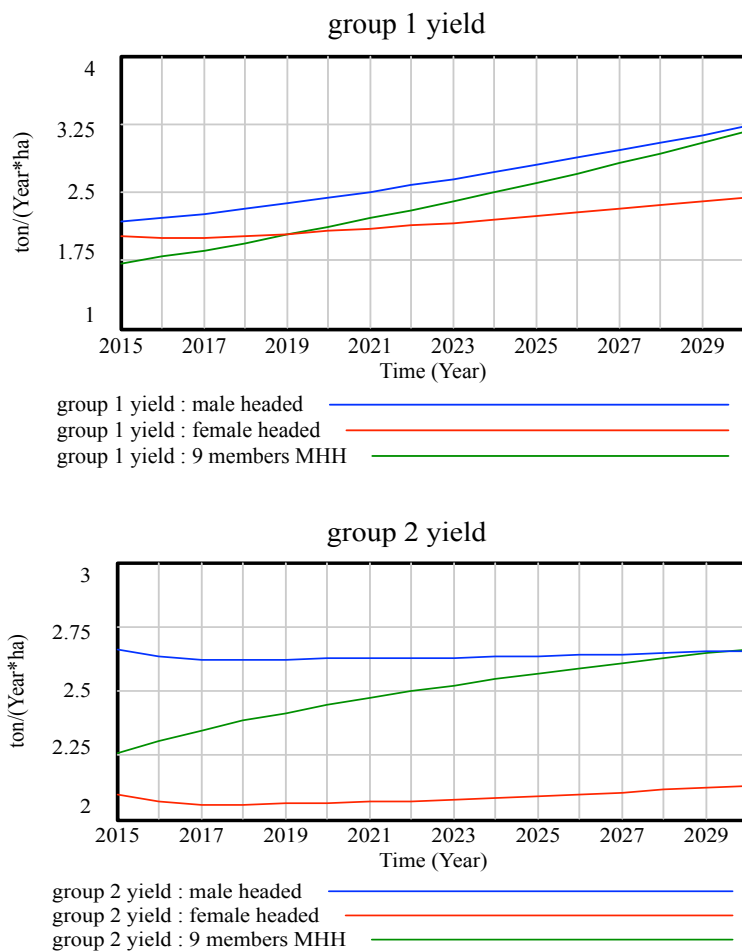


Figure 29 – Model output - Group 1 and Group 2 yields

As no fertilizer is applied to Group 3, these crops rely only on the nitrogen naturally added to the soil, and the nitrogen present on crop residues from the previous growing season, leading to low yields, and minor increase overtime. Group 3 yields are similar for all three households, an average of 1 ton/ha throughout the simulation.

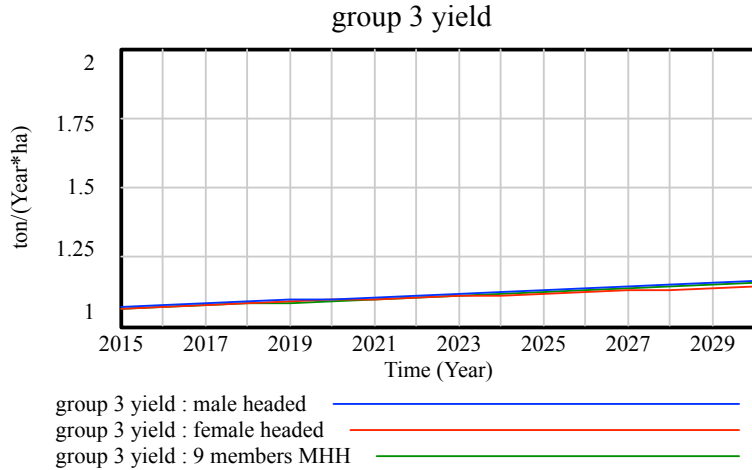


Figure 30 – Model output - Group 3 yield

5.6.4. Soil Dynamics Outputs

Soil dynamics and yield are strongly connected. Yield highly depends on soil organic matter, as it retains water from precipitation, positively influencing the water intake by plants (Bot & Benites, 2005). The amount of SOM depends on the amount of residues left on the field, meaning that higher yields leads to more biomass, and thus greater amounts of SOM. As the MHH have higher Group 1 yields, the amount of SOM in Group 1 field is higher than in the FHH. The initial SOM value was considered equal for both households, however, this value differently increases. The MHH increases the SOM in Group 1 field from 35,5 ton/ha in 2015, from 54 ton/ha in 2030. Yet the FHH increases the same value to 47 ton/ha. The household with 9 members follows similar path, and surpass the FHH in 2023, reaching 51 ton/ha of SOM in 2030.

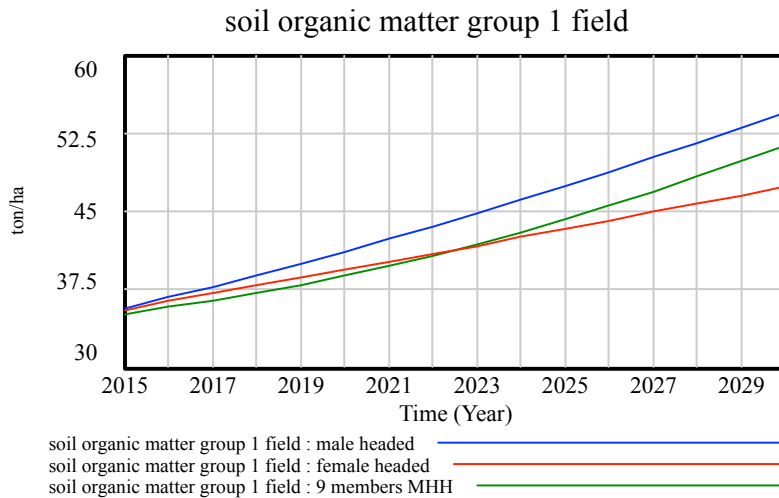


Figure 31 – Soil organic matter group 1 field

The SOM in Group 2 field varies different in all three households due to the yields. The low Group 2 yields in the FHH leads to a low input of soil organic carbon in the field, and thus the SOM level in Group 2 field slightly decreases overtime. In the MHH and the household with 9 members, the SOM in the Group 2 field accumulates overtime, increasing from the initial 45 ton/ha to 49 ton/ha for the prior, and to 48 ton/ha for the later.

Additionally, no fertilizer is applied to Group 3 crops, causing low yields, and thus little input in SOM. The plants use SOM in the growing process, making the output of SOM in the soil higher than the input, decreasing the SOM level in Group 3 field over time.

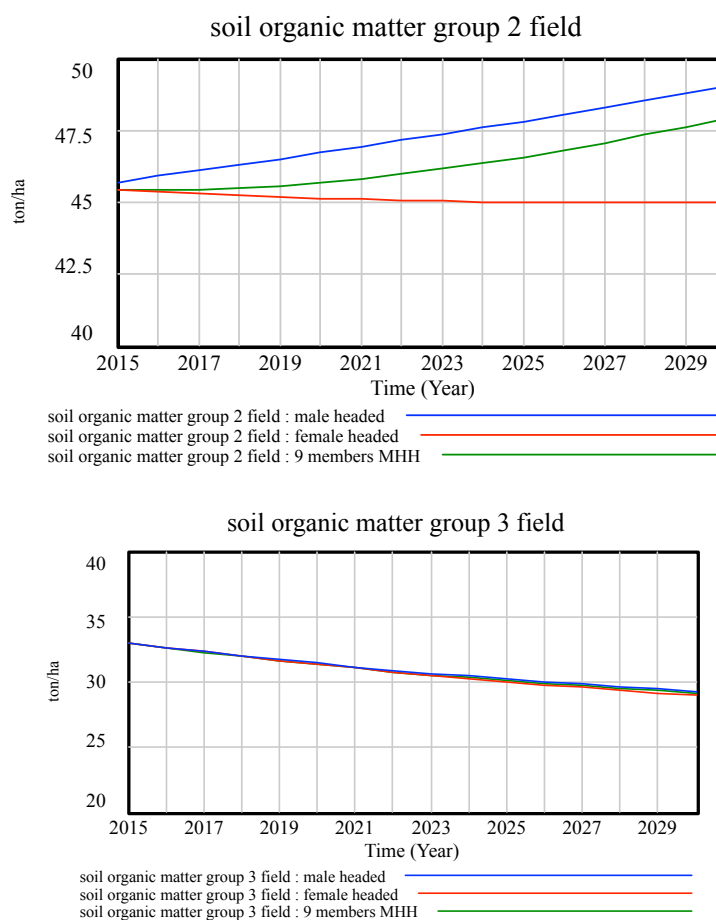


Figure 32 – Model output – Soil organic matter Group 3 and Group 3 fields

5.6.5. Sales Decisions Outputs

Farmers decisions of how much of their production they should sell is based on the perceived profitability and perceived food supply. Farmers weight up these factors and decide to sell part of their production. As food supply for the three households is rising, the share of production sold increases. In the other hand, if farmers perceive a higher profitability from crop sales, they will tend to sell more of

their production. Additionally, MHHs tend to sell more of their production than FHHs.

The MHH sells 50% of the Group 1 production in 2015, which is approximately 1 ton, increasing to 56% in 2030, which is almost 3 ton. As the FHH have lower yields and production, the amount of production sold is considerable lower than the MHH. In 2015, the FHH sells 40% of their Group 1 production, which is approximately 0,55 ton, increasing it to 44% in 2030, which is less than 1,5 ton, and near half of that amount sold by the MHH. The household with 9 members perceive a significant lower food adequacy, and thus retain more of the production, decreasing the share of production sold from 46% in 2015 to 39% in 2030.

Concerning Group 2, the difference between all three households is less discrepant. The MHH sells 25% of Group 2 production in 2015, which is approximately 230 kg, increasing it to 32% in 2030, nearly 1 ton. The FHH sells 20% of their Group 2 production in 2015, which is approximately 180 kg, increasing it to 25% in 2030, which is over 600 kg. The household with 9 members initially produces more than the MHH, due to a larger farm land size, yet increases less, and sells approximately 600 kg in 2030.

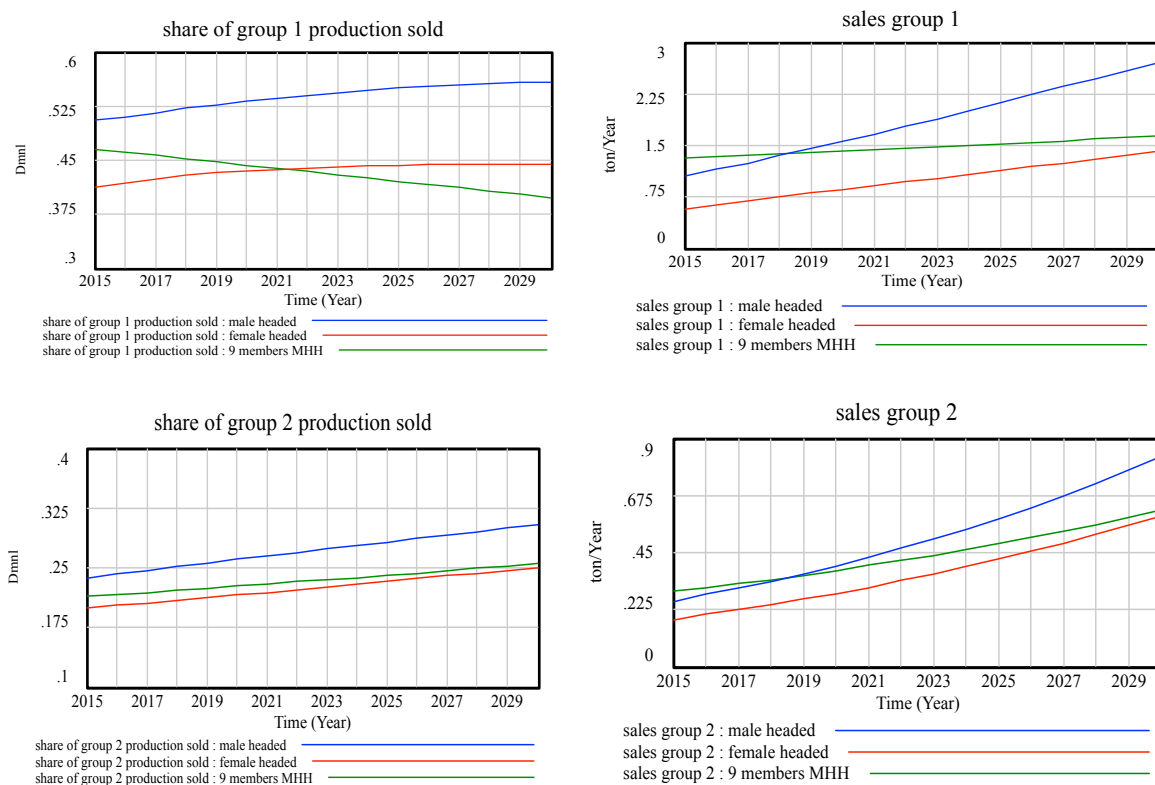


Figure 33 – Model outputs – Share of production sold and sales for Group 1 and Group 2

5.6.6. Household Income and Expenditure Outputs

The aggregated farm income represents the sum of all farm income sources – crop production sales, and off-farm income. As previously mentioned, the FHH have lower off-farm incomes than the MHH (Central Statistical Office, 2012b) , and also may sell their production with lower prices (Pitamber, 2006). This causes the FHH to have significant lower aggregated farm income comparing to the MHH. The simulation displays that in 2015, the MHH has an aggregated farm income of approximately US\$1000, and the FHH has US\$750, a 25% lower value. The MHH significant increase the income, and nearly reach US\$3000 in 2030, almost tripling the initial value. However, as the FHH faces more constrains, the income does not increase as much as the MHH, reaching approximately US\$1900 in 2030, a 35% lower value. Additionally, the household with 9 members follows similar path as the MHH.

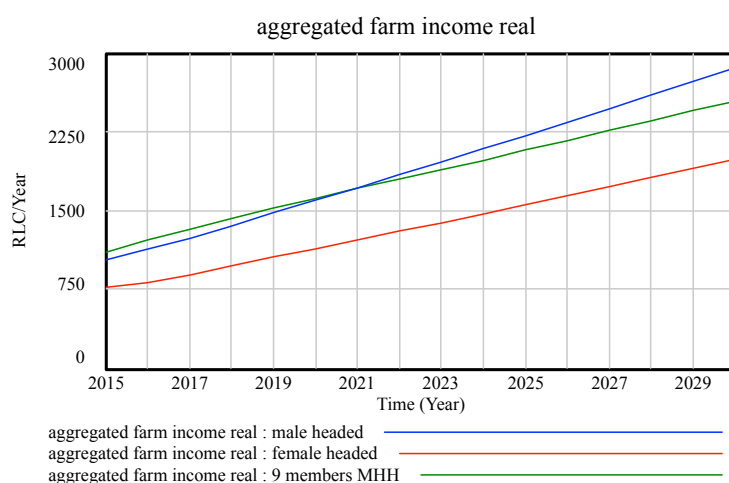


Figure 34 – Model output – Aggregated farm income

The two major farm expenditures are in food and fertilizer. Food expenditure accounts for 60% of the total farm expenditure, and the remnant is divided for other needs, such as fertilizer and soil improvement. As the MHH aggregated farm income is higher than the FHH, the expenditures will also be higher. The MHH expends US\$600 for purchasing food in 2015, increasing this value to US\$1700 in 2030. The FHH expends US\$480 in 2015, increasing to US\$1200 in 2030.

The difference in fertilizer expenditure is more noticeable, as the FHH allocates less income for purchasing fertilizer. The MHH initially expends US\$150 in fertilizer, increasing to US\$430 in 2030. The FHH initially expends US\$90, increasing to US\$220 in 2030, nearly half of the MHH fertilizer expenditure.

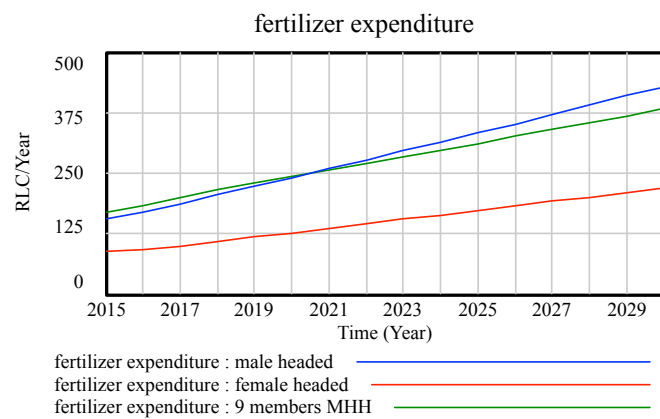
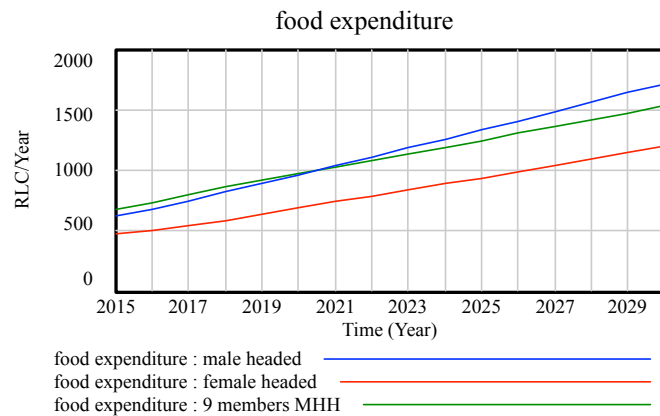


Figure 35 – Model outputs – Food and fertilizer expenditures

5.6.7. Food Availability Outputs

All the previous dynamics described above influences the outputs of the food availability sector. Different households' decisions reflect on the availability of food, and it reflects in the farm decisions. **Figure 36** displays the total household availability of food in kcal per capita per day. This variable is the sum of the availability of food from Group 1 and Group 2 crops, as well as from purchased food.

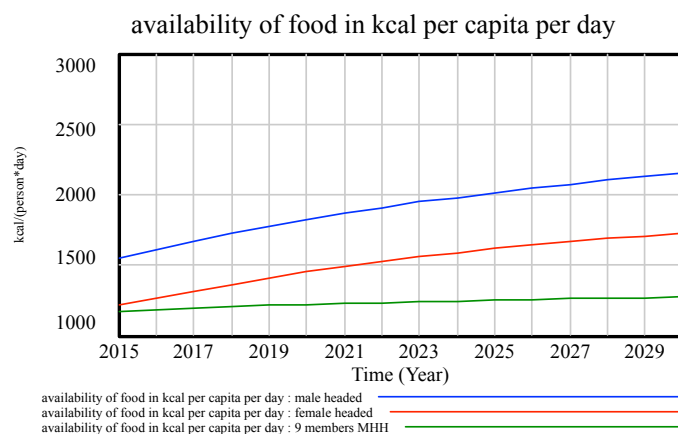


Figure 36 – Model output – Availability of food (kcal/capita/day)

The graph clearly displays the effects of gender inequality in the availability of food. Not only the FHH initially has less available food, but also do not increase as much as the MHH. The MHH initially has 1500 kcal/capita/day, increasing to approximately 2100 kcal/capita/day in 2030. The FHH initially has 1200 kcal/capita/day, increasing to approximately 1700 kcal/capita/day in 2030. The household with 9 members struggles to increase the availability of food, and maintain less than 1200 kcal/capita/day throughout the simulation process.

Figure 37 displays the dietary energy availability of food from the Group 1 production. Group 1 crops are the main source of the energy intake of an individuals' diet. For the MHH the initial value is approximately 900 kcal/capita/day, and increases to over 1200 kcal/capita/day in 2030. Comparing to the MHH, the FHH has available 200 kcal/capita/day less, and initially counts with 700 kcal/capita/day, increasing to 1000 kcal/capita/day in 2030.

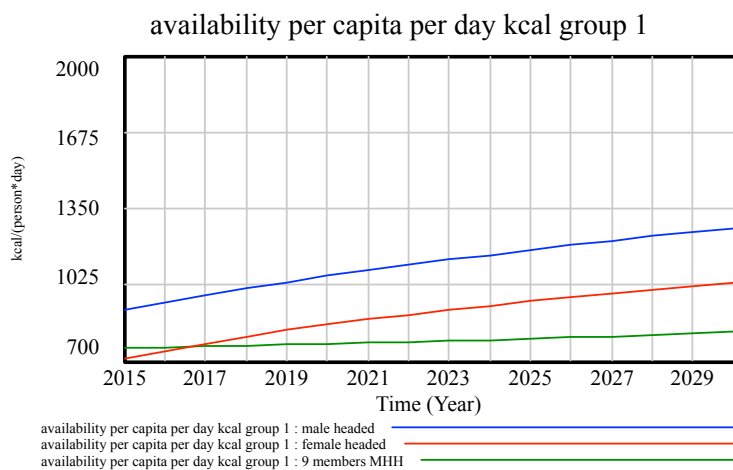


Figure 37 – Model output - Group 1 availability of food (kcal/capita/day)

Group 2 crops are less caloric than Group 1 crops, and are a secondary source of dietary energy. The difference between the two households in the availability of food from Group 2 crops is less discrepant comparing to the Group 1 crops. For the MHH the initial value is approximately 210 kcal/capita/day, and increases to over 320 kcal/capita/day in 2030. Comparing to the MHH, the FHH has available only 200 kcal/capita/day less, and initially counts with 190 kcal/capita/day, increasing to 300 kcal/capita/day in 2030.

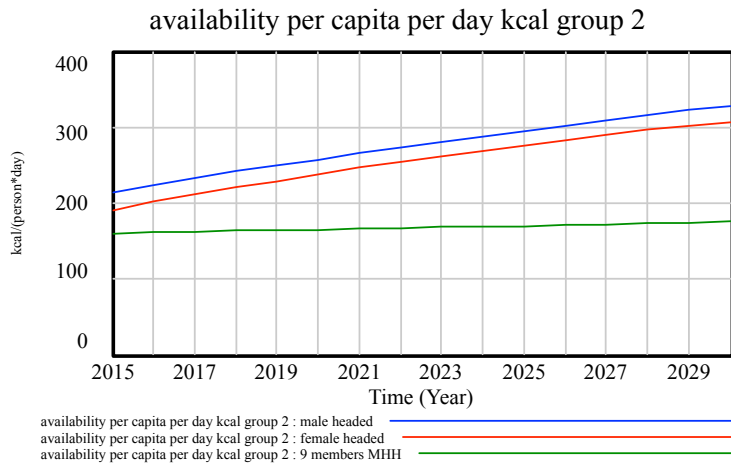


Figure 38 - Model output - Group 2 availability of food (kcal/capita/day)

Another important source of food is the purchased food, which is responsible to diversify the households' members diet. Purchasing food baskets is a common practice, and the more food baskets a household can afford, the less is the risk of being food insecure. **Figure 39** presents the amount of food baskets each household can afford over the years. The FHH initially affords an average of 1,7 food baskets per year. The MHH and the 9 members MHH are able to afford 2,5 food baskets. All three households are able to increase the number of purchased food baskets, but the FHH is the household that can least afford food baskets, with an average of 3,2 in 2030. The MHH nearly reaches 5 food baskets in 2030, and the 9 members MHH slightly over 4 food baskets.

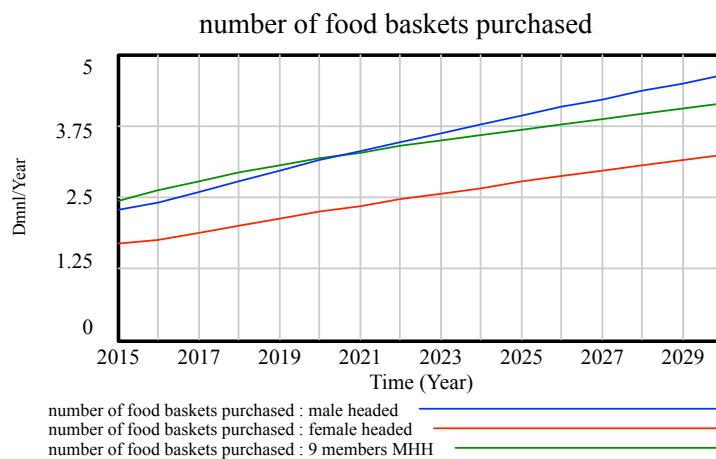


Figure 39 – Model output - Number of purchased food baskets per year

Although the MHH and the 9 member MHH purchase comparable quantities of food baskets over the years, the number of household members is crucial when sharing the available food. The MHH initially has available 420 kcal/capita/day from food baskets, the FHH 310 kcal/capita/day, and the 9 member MHH 250 kcal/capita/day. The 9 members MHH not only has the least available food from

food baskets, but also is not able to increase this value over the years. The MHH has available 550 kcal/capita/day in 2030, and the FHH has 390 kcal/capita/day.

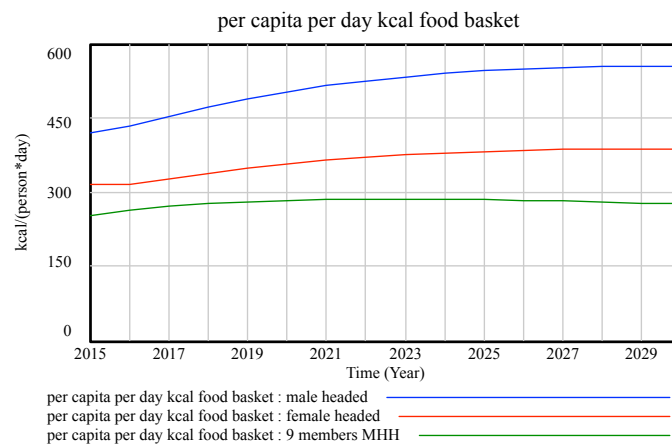


Figure 40 - Model output - Availability of food from food baskets (kcal/capita/day)

5.7. Assessing Food Insecurity

Although the output indicator express the availability of food as an annual average value, implying that households may have periods with a higher or lower availability of food during the year, Devereux (2006) states that accurate information on the intensity or severity of food insecurity is more important and urgent in an emergency programming context than the duration of food insecurity: it is more critical to know the magnitude of the food gap than for how long the affected population has faced this food gap.

There are several approaches to assess food security, using different indicators, and one of the simplest ways to assess intensities of food insecurity is in terms of levels of food intake (Devereux, 2006). Taking 2100 kcal/capita/day as an average daily energy requirement, the following categories of food insecurity can be defined:

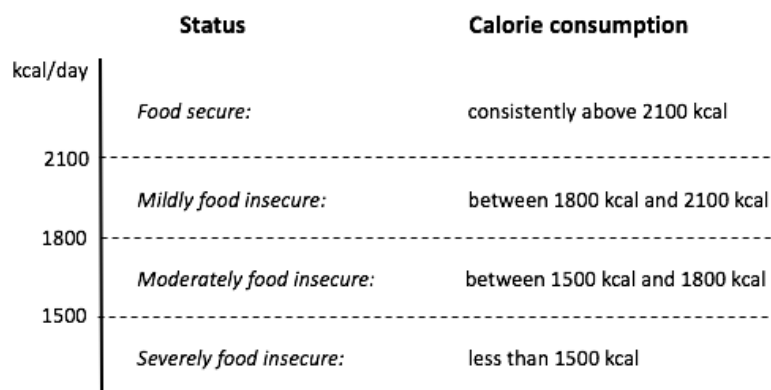


Figure 41 – Food security levels (Source: Devereux, 2006)

Figure 42 presents the insecurity severity levels of the three households over the simulation period.

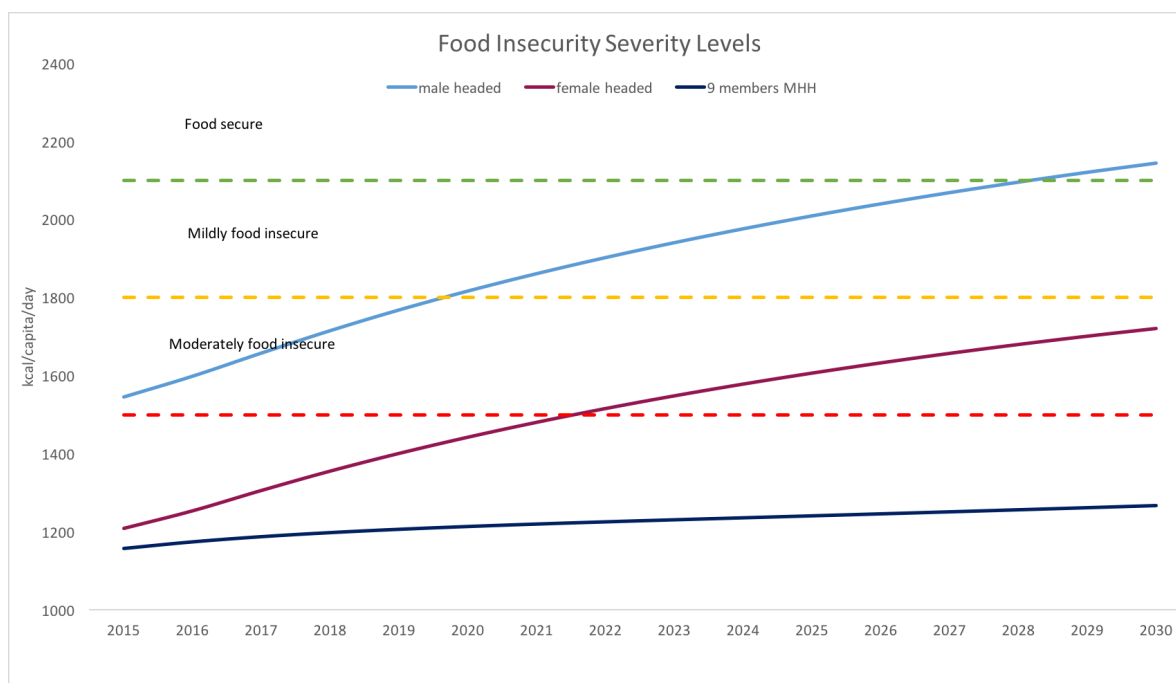


Figure 42 – Model outputs – Food security levels

As the **figure 42** presents, the MHH begins the simulation with the “moderately food insecure” status, and in 2020 reaches the “mildly food insecure”, continuing with this status during 8 years, when in 2028 reaches the “food secure” status. The FHH is initially assessed as “severely food insecure”, and in 2022 reaches the “moderately food insecure” status, yet the FHH do not overcome this status until the end of the simulation period. Finally, the 9 members MHH remains with the “severely food insecure” status throughout the entire simulation period.

5.8. Assessing Poverty

Poverty levels in Zambia are significantly high, and it has continued to be more of a rural than an urban phenomenon. The majority of the poor have continued to face extreme levels of poverty particularly in rural parts of the country. Households headed by females are more likely to be impoverished than their male counterparts. Levels of poverty are more likely to be higher among larger and elderly headed households. (Central Statistical Office, 2012b).

The official poverty line used in Zambia is based on data from the Living Conditions Monitoring Survey published by the Central Statistics Office. In 2012, the official food poverty line (also known as the extreme poverty line) was set at 96 366 Zambian Kwacha (K) per month for a household of six persons (equivalent to 18,72 US dollars (\$), or around \$0,62 per person per day). The official absolute

poverty line was K146 009 (equivalent to \$28,36, or around \$0,94 per person per day). Values in this summary use the 2012 exchange rate of K5147 to \$1 (The World Bank, 2016).

Figure 43 displays that in 2010, 60,5% of the total population lived below the absolute poverty line (\$0.94/capita/day). This reality was even more present in rural areas, where 77,9% of the population lived below this line. A minor improvement is notable from 2006 to 2010, with a difference of less of 3% leaving achieving to overpass the poverty line.

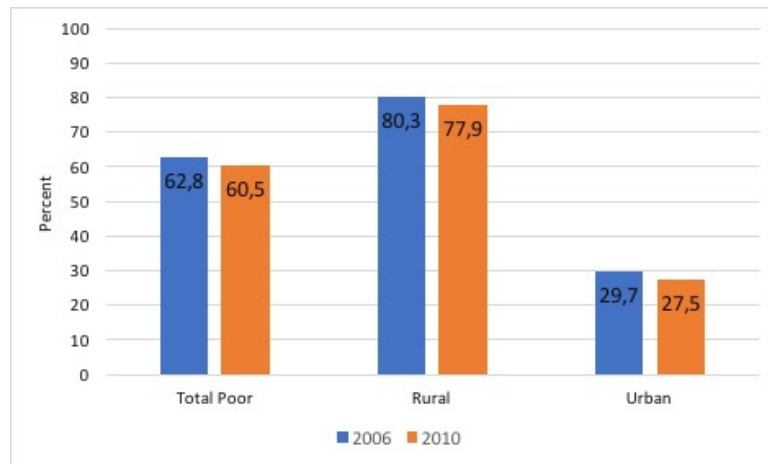


Figure 43 – Incidence of poverty in Zambia (Source: CSO, 2012b)

Figure 44 presents the poverty status concerning the gender of the household head. In 2010, 41,9% of male headed households and 44,4% of female headed households were below the extreme poverty line (living with less than \$0,62 per capita per day). This represents that female headed households are more likely to live in extreme poverty than male headed households.

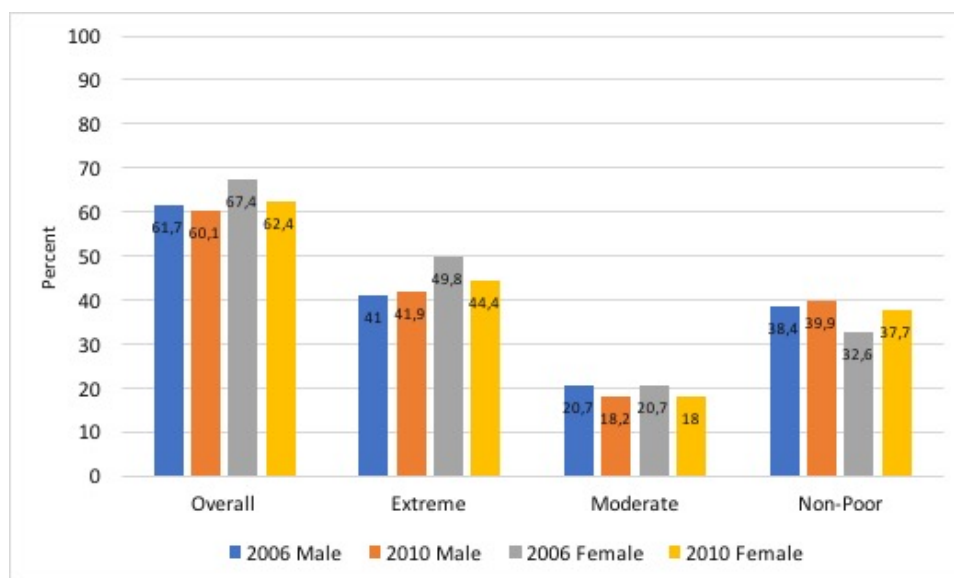


Figure 44 – Poverty status and gender of the household head (Source: CSO, 2012b)

Figure 45 presents the poverty levels of the three households during the simulation period.

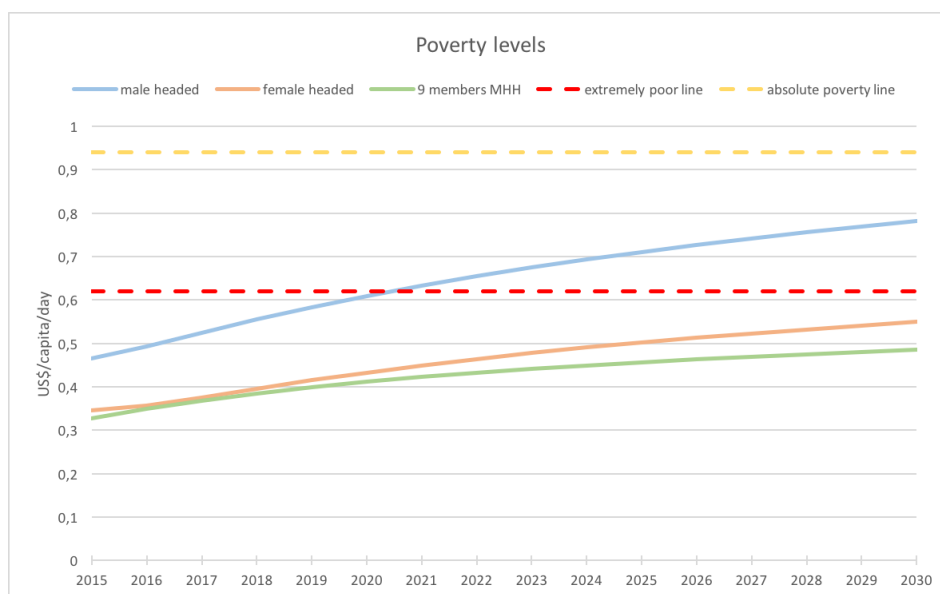


Figure 45 – Model output – Poverty status

As the **figure 45** presents, the MHH begins the simulation below the extremely poverty line, and in 2020 surpass this line. Noting that at the same year the MHH switches from “moderately food insecure” to “mildly food insecure”. Yet the MHH stays below the absolute poverty line throughout the entire simulation period. Additionally, the FHH and the household with 9 members both stay below the extremely poverty line during the 15 years of simulation period.

5.9. Policy Design

From the analysis of the system’s structure and model’s behavior, it is notable that none of the three scenarios outcomes represent a desired household welfare, and that female headed and larger households struggle to overcome poverty and achieve a moderate level of food security. Moreover, when comparing the outputs of a common male headed household to the other household types, the model outputs shows that having access to agriculture inputs, especially fertilizer, plays an important role on increasing the household food security.

That said, the model was used to test possible interventions to improve food security of the most disadvantaged households. The results of these strategies are presented below and aim to understand whether these households can achieve a better level of food security.

It is important to mention that these interventions are merely demonstrative, aiming to better understand their possible impact on the food security reality of Zambia, and do not represent actual policy options since the viability requires a more accurate assessment from policy makers and relevant stakeholders.

5.9.1. Conservative Agriculture

As previously mentioned, most farmers remove crop residues through burning or animal feeding (Verhulsta et al., 2010), leaving small quantities on the field. As explained in the Soil Dynamics sector, the residues improve the quality of the soil, and retain nitrogen from the previous growing season, which affects the overall health and improves plant growth (Bot & Benites, 2005).

The model structure represents the common dynamics in a farm, which is the removal of residues. However, one of the practices that has been promoted in Zambia is the conservation agriculture (CA), which promotes a different technique of farming. The technique involves land preparation using minimum tillage methods, nitrogen-fixing crop rotation, and retention of crop residues from the prior harvest (Haggblade & Tembo, 2003a). Projects such as the Conservation Agriculture Programme (CAP1) have been responsible to support farmers to adhere this technique, and positive effects on food security has been achieved (Aune et al., 2012).

Although the model does not contain structure to represent tillage methods and crop rotation, the dynamics of crop residues is present in the model. The reference share of plant residues removed from the field is 70%, and is influenced by the soil improvement expenditure. That said, it is possible to evaluate the impact of the retention of crop residues on the field, which is one of the practices in conservation agriculture.

Three indicators were selected to express the main effects of CA on the farm dynamics: yield, farm income, and availability of food (kcal/capita/day). The simulations marked with “BaU” are the outputs previous described, showing the business as usual dynamics. The simulations market with “CA” represents the conservation agriculture results. **Figure 46** represents the outputs for this strategy.

As expected, as soon as the conservation agriculture practice is introduced, the nitrogen in plant residues increases significantly. A higher availability of nitrogen leads to higher yields, and thus farmers can sell more of their production. The availability of food is positively affected by the yield, and by the farm income, as farmers can afford to buy more food baskets. Therefore, both households significantly increase the availability of food when practicing the retention of crop residues, and the

values reached in 2030 is, for both households, approximately 200 kcal/capita/day more than the business as usual dynamics.

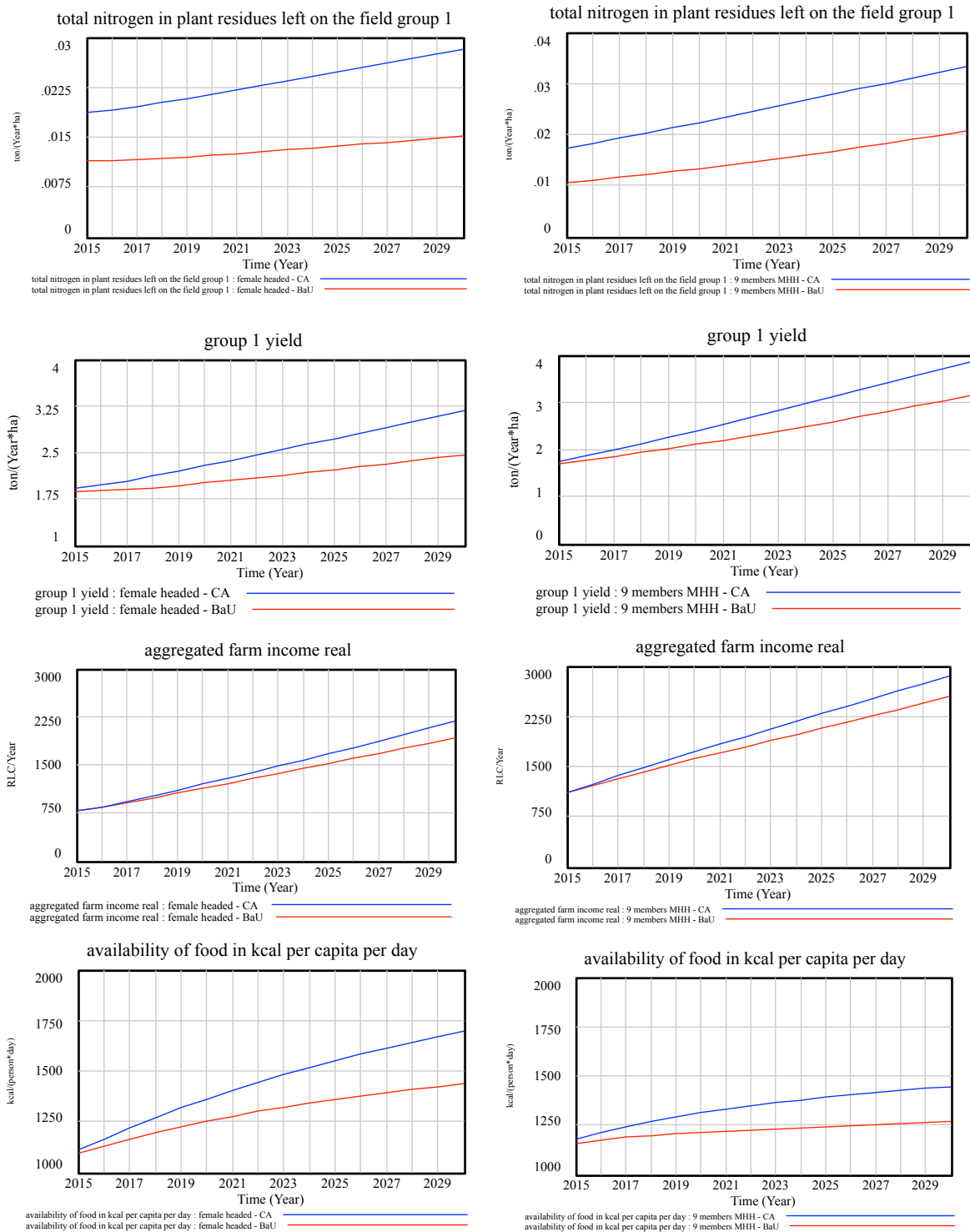


Figure 46 – Model outputs – Conservation agriculture strategy

5.9.2. More Access to Fertilizer

As previously mentioned, female headed households do not have the same access to agriculture inputs as male headed households, causing lower yields and income, and thus a higher risk to be food insecure (García, 2013). Furthermore, a large family size has negative impact on house food security. The larger the family size the lesser food availability to each person within the household and nutritional status is affected (Olayemi, 2012).

That said, intensifying efforts on fertilizer distribution to female headed and larger households can help these families increase availability of food, and thus increase food security. That said, the following outputs represent two strategies based on fertilizer distribution: 1) provides 30% more subsidized fertilizer to female headed households than is usually provided for a male headed household, and 2) provides fertilizer based on the number of household members.

The graphs on the left display the results for the case in which the FHH receives a constant quantity of fertilizer every year. The amount provided to the FHH in this strategy is 108 kg of nitrogen fertilizer, 30% more of what is usually provided to male households, which is 90 kg. The graphs on the right display the results for the case in which the household receives fertilizer according to the number of members. The base is 90 kg of fertilizer for a family up to 5 members, and an increase of 10% is provided for each new household member.

As expected, subsidizing more fertilizer, quickly and significantly contributes to increase yields. Fertilizer provides a high amount of nitrogen, and a higher availability of nitrogen leads to higher yields, and thus farmers have more available production to consume and sell. The availability of food is positively affected by yield and farm income, as farmers can afford to buy more food baskets. Therefore, both households significantly increase the availability of food when more fertilizer is available.

For the FHH, as the fertilizer strategy provides a constant quantity of fertilizer over the simulation period, the yields, and thus the food availability, increase in the same proportion. For the household with 9 members, which was applied the strategy of providing fertilizer per household member, the quantity of nitrogen increases due to a growing household size, and thus yield and food availability increase in a different rate over the simulation period.

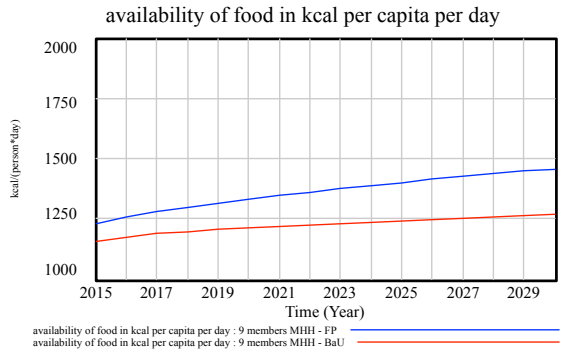
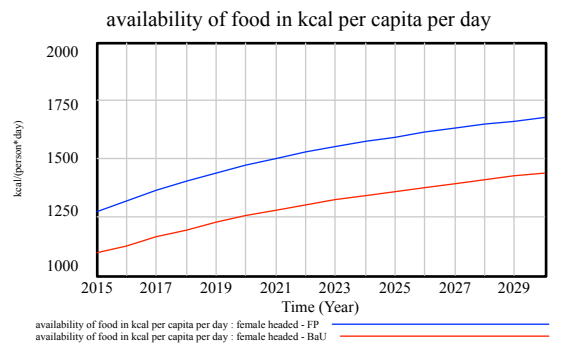
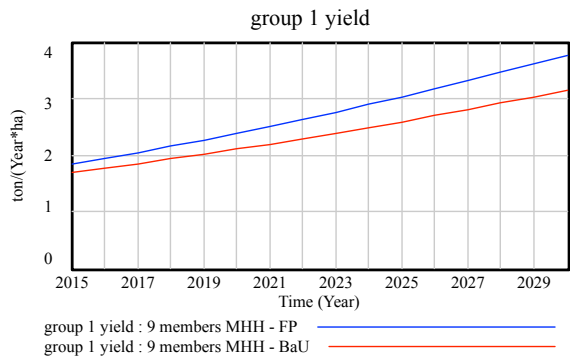
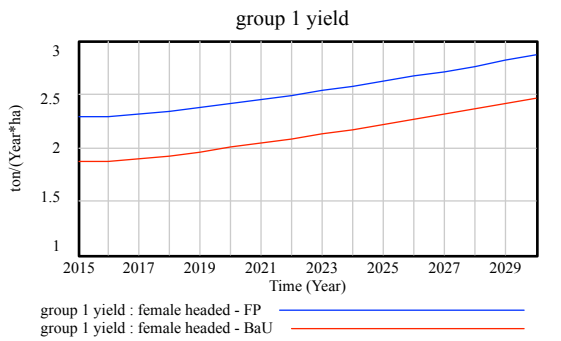
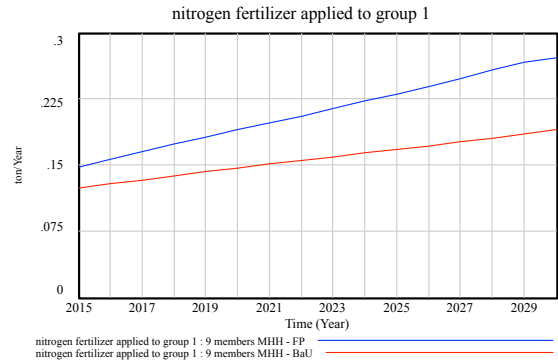
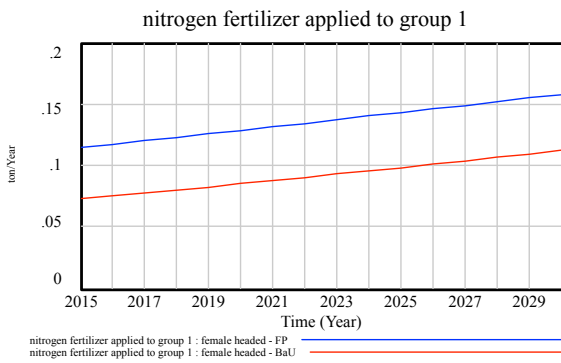


Figure 47 – Model outputs – Fertilizer strategy

5.10. Answer to Research Question (4)

The fourth and last research question intends to suggest solutions to increase food availability and thus diminish food insecurity:

4) What are possible strategies that can be adopted to diminish food insecurity in subsistence farming?

The studied scenarios suggested that female headed and large households struggle to overcome poverty and achieve a moderate level of food security. The outputs reveal that having access to agriculture inputs, specially fertilizer, plays an important role on increasing the household food security. Therefore, the model was used to test possible solutions to improve food security most disadvantaged households.

Three suggestions were tested and demonstrate to be reliable intervention to increase food availability:

- 1) Conservation Agriculture:** The technique of keeping crop residues on the soil after harvesting, which improve the quality of the soil and retain nitrogen, proved to be a good strategy. However, although the availability of food increases, the households still not able to reach a desirable food security level.
- 2) More Access to Fertilizer:** In developing countries like Zambia, farmers have poor access to resources, especially fertilizer. Female headed households face even higher constrains and large households suffer with the low productivity. Therefore, the strategy of distributing additional amount of fertilizer to female headed households and larger households demonstrated to be a suitable policy, increasing food availability, although the desirable food security level was not reached.

6. Conclusions

This research consisted on the development of a system dynamics model containing structure that represents the subsistence farming from the beginning to the end of the system. It contains the identification of factors affecting farmers' crop decisions and farm management relationships, applied to a system dynamics model that aims to explain the problem of food security at the household level.

The first two research questions ("What are the factors that influence smallholding farmers crop decision?" & "What are main relationships involved in subsistence farming?") were focused on the procedure of statistical analysis to identify factors affecting farm decisions. This initial step allowed to identify and better understand the subsistence farming dynamics, and the findings in this stage were then applied to a system dynamics model aiming to represent the reality of small farms in Zambia. The literature review, framework, and statistical analysis prepared in this first stage, gathers significant information, not only for the system dynamics model developed for this thesis, but also for further consultation in future researches aiming to study the subsistence farming.

The data used in the statistical analysis to identify the relationships in a farming system was collected in a follow up survey of the Conservation Agriculture Project in 2015, and several correlations were found regarding different types of capital, such as human, natural and financial. Factors such as available labor, size of the household, age of the household head, farm land size, perceived soil fertility, and wealth level, were found to influence crop decisions. Additionally, relationships not direct related to crop decisions were also found, providing an improved framework to understand the entire farm system.

The answer for the third research question ("What is the structure and main feedback loops that explain the food security phenomenon in subsistence farming?") addresses the dynamics of subsistence farming in Zambia through a system dynamics model. The links between variables represent what is believed to be a causal relationship, mimicking the structure of the real system, and behaving the same way the real system would. For this to be valid, the structure needs to be well funded with different types of data – numerical, written, and mental. The model structure was built upon literature basement, and the performed statistical analysis was a first step to identify decisions determinants, and relationships that was unknown before.

The model developed in this thesis was based in a previous developed model, which was modified, amplified and further developed intending to represent the entire subsistence farm system, and allowed the assessment of food security at the household level, including different crops, decisions and resources. The model contains sectors that characterize each of the main dynamics of the system,

representing dynamics such as crop decisions, yield and production, food availability, and household income and expenditure. This allowed to assess food security not only with food-related variables, but also with variables that influence the availability of food, a crucial asset to decision-making and policy design.

The representation of the identified decision determinants in the model, allowed to demonstrate the usefulness of integrating collected data into a system dynamics model to understand the dynamics of subsistence farming, and thus assess food security. This process helped to develop the model structure and feedback loops that explain the effect of farm decisions on the household food availability, and select the key indicators that support the food security assessment.

The base model used in the present research was designed to assess the maize supply and demand at the country level, and was modified and complemented in several segments to display the dynamics at the household level, counting with structure for numerous elements of a common subsistence farm in Zambia. The process of building the model included the selection of causalities, identified in the first research stage, and further literature investigation. The model contains several variables that are indicators to assess household food security, and the results displayed in this thesis contain relevant information to understand these dynamics. Furthermore, this stage was concluded with the evaluation of possible strategies to increase food security.

The first stage allowed to perceive that the size of the household and the gender of the households' head are two factors that strongly influence a subsistence farming system. After the identification, the investigation of such reality provided key insights for building the model's structure, allowing the model to represent the differences between male headed, and female headed households. The decision to simulate the model with scenarios which the gender of the households' head differs, proved to be significant, as the output for such households turned to be notorious different, with the female headed household having consistent lower outcomes. Nonetheless, the scenario in which the household starts with a higher number of members, displayed that these types of households are the ones that most struggle to be food secure.

As it was seen throughout the analysis, one of the main determinants of farm decisions and different outcomes is the availability of fertilizer, which reflects on the entire farm dynamics. This relationship was explained through a reinforcing feedback loop in which the more available fertilizer, the higher the yields, and thus higher farm income and available food. Furthermore, crop decisions are highly and directed influenced by the availability of food, and the perceived crop profit. Strategies aiming to diversify crop production should aim into these specific factors or secondary factors that influence crop decisions, such as fertilizer.

The fourth and last research question (“What are possible strategies that can be adopted to diminish food insecurity in subsistence farming?”) find solutions to increase food availability and thus diminish food insecurity. The model integrates relevant theories to investigate the impacts of fertilizer subsidy program, and two demonstrative interventions were tested in the model intending to increase household food security: 1) Introduction of the conservation agriculture technique of crop residue retention, and 2) Provide subsidized fertilizer according to the gender of the households’ head, and according to the number of the households’ members. Both strategies appear to be a viable method to increase the availability of food, however, the strategies proposed do not increase household food security to a satisfactory level.

Providing more fertilizer is a viable way to enhance soil fertility, yields and crops production. However, providing only fertilizer fails to build up soil organic matter levels adequately, limiting the improvement of crop production in a long-term. Soil organic matter is an imperative element for a resilient crop production. Alternative strategies, such as the conservation agriculture, that add organic matter to the soil are more suitable than fertilizer programs when considering long-term production, and thus food security. These findings contribute to strength and support the conservation agriculture technique as an appropriate manner to increase food security.

This study has taken an approach that offers an ample vision of a system, providing significant more information than mere mathematical models that display only a specific subject of a complex system. This thesis contributes to add a new perspective on the decision-making and policy design, and includes elements from the beginning to the end of the agriculture process, from crop decisions to availability of food. Strategies aiming to raise food security can be applied in several levels, and regard different key influencing variables. The results display the potential of this unique approach, and structuring knowledge into a broader and dynamics context can contest conventional suppositions.

Lastly, this study focused on the agriculture production process of a subsistence farm, and mainly includes variables related to this field. However, future research could add additional mechanisms to assess the impact of different elements, such as education, health, and access to basic needs. For example, poverty and nutritional status could be represented in more detail, aiming to express the impact of policies on achieving the intended goals. Overall, this research represents the usefulness of system dynamics models and creates a starting point for future work that aims to evaluate the impact of farm decisions in the availability of food, as well as the sustainability of agriculture strategies intending to raise food security.

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Appendix

A.1. Detailed Statistical Analysis Results

Different statistical approaches were used to analyze factors influencing farmers' crop decisions. Firstly, comparison of means was conducted to explore differences between groups of categorical variables, such as districts, and wealth level. T-tests were used for variables with two categories, and ANOVA for variables with three or more categories. Secondly, linear regressions were carried to explore relationships between each of the main study variables and the continue variable.

A.1.1. T-tests Results

The gender of household's head was found to be a significant factor. On average, male-headed households dispose a smaller share ($0,23 \pm 0,02$) for crops of Group 2, than female headed households ($0,32 \pm 0,03$) (mean \pm S.E.). This difference, 0,9, is significant $t(90) = -2,51$, $p = 0,014$, and represents a medium effect size, $d = -0,61$.

There was significant difference in the share of Group 3 between the three districts ($F(10, 30) = 10$, $p = 0,000$), and represents a large effect size, $\omega^2 = 0,20$. The assumption for equal variances was violated. Thus post-hoc comparisons were performed using the Games-Howell test, and indicated that the average share of cash crops in Chibombo ($0,14 \pm 0,02$) was significantly different from Mumbwa ($0,27 \pm .04$), and Chipata ($0,30 \pm 0,04$). However, Chipata and Mumbwa did not differ significantly from each other ($p = 0,768$).

Counter-intuitively, there was not a significant difference between the wealth levels for the share of Group 3, as it was expected that the wealthier the household, the greater the share of cash crops. However, it was found a significant difference for the share of Group 2 ($F(3, 88) = 9,23$, $p = 0,000$, $\omega^2 = 0,21$). Post-hoc comparisons using Tukey HSD test indicated that the average share for wealth level Above Average ($0,16 \pm 0,02$) was significantly different from Medium ($0,30 \pm 0,03$), Below Average ($0,36 \pm 0,03$), and Low ($0,29 \pm 0,03$). The latter three groups did not differ significantly from each other ($p > 0,05$).

A.1.2. ANOVA Results

Averages for Group 1 were significantly different according to the rotation practice in the previous growing season ($t(111) = 2,43$, $p = 0,017$), with a large size effect, $d = 0,77$. Households that did not practice crop rotation disposes of a higher share of crops of Group 1 ($0,79 \pm 0,07$) than those who practiced crop rotation ($0,64 \pm 0,02$).

Linear regression results indicate that the age of the household's head is significant and negative related to the share of Group 3 ($r = -0,351$). The model explains 12% of the variance ($r^2 = 0,122$), and suites the data ($F(1, 47) = 6,524, p = 0,014$).

A.1.3. Linear Regressions Results

Additionally, linear regression reveals that the size of the household is significant and negative related to the share of Group 2 ($r = -0,211$) and Group 3 ($r = -0,325$). Although no significant relationship was found with Group 1, results did find a significant relationship between household size and the Share Index ($r = -0,377$), meaning that the relationship moves towards 0, raising the share of Group 1.

The model of Group 2 vs. household size explains a slight amount of the variance, only 5% ($R^2 = 0,05$), and fits the data ($F(1, 85) = 3,962, p = 0,05$). The model for Group 2 vs. household size explains 11% of the variance ($R^2 = 0,112$) and fits the data ($F(1, 45) = 5,685, p = 0,021$). The model of Share Index vs. household size explains a slight more amount of variance, 14% ($R^2 = 0,142$) and also fits the data $F(1, 38) = 6,281, p = 0,017$.

The assessment of soil fertility is negatively related to the share of Group 3 crops ($r = -0,317$). The linear model ($F(1, 47) = 5,251, p = 0,026$) explains 10% of the variance ($R^2 = 0,100$) and suggests that the better the quality of the soil, the less is the share of cash crops. Although the correlation with the share of Group 1 crops was not significant ($p = 0,12$), it indicates a slight positive correlation ($r = 0,148$) alluding that farmers plant more crops of Group 1 rather than Group 3 when the quality of the soil is better.

Availability of labor revealed to be an important factor influencing decisions as three workforce-related variables were significant in regressions. The size of household is negatively related to the shares of Group 2 ($r = -0,211$) and Group 3 ($r = -0,335$), as well as the Share Index ($-0,377$). However, the variance explained by the models is small. The regression with Group 2 ($F(1, 85) = 3,962, p = 0,05$) explained 5% of the variance ($R^2 = 0,045$), and with Group 3 ($F(1, 45), p = 0,021$) explained 11% ($R^2 = 0,112$). The Share Index was again able to detect the decisions direction as the linear regression was significant ($F(1, 38) = 6,281, p = 0,017$), and explained 14% of the variance ($R^2 = 0,142$).

The regression with the total labor force clearly evidences the workforce allocation, as all three regressions were significant. Group 1 is the only group with a positive correlation ($r = 0,257$), and the regression ($F(1, 105) = 9,858, p = 0,002$) explained 9% of the variance ($R^2 = 0,086$). Group 2 is

negative related (-0,316), the regression $F(1, 84) = 9,302, p = 0,003$ explained 10% of the variance ($R^2 = 0,10$). Group 3 is also negative related ($R^2 = -0,354$), the regression ($F(1, 42) = 6,01, p = 0,018$) explains 12% of the variance ($R^2 = 0,125$). The Share Index confirms the previous regressions, and was also significant and negative related ($r = -0,532$), the regression ($F(1, 35) = 13,817, p = 0,001$), and explained 28% of the variance ($R^2 = 0,283$).

A.2. Full Model Documentation

A.2.1. Sector: Yield Group 1

Above Ground Dry Matter group 1=

Plant Residue Above Ground Dry Matter+yield group 1 dry matter

Units: ton/(Year*ha)

This variable represents the total amount of dry matter production above ground (including all plant parts, also yield).

AREA HARVESTED group 1 per farm=

total planted area*Share Group 1

Units: ha

This variable represents the area on which maize is produced. Note that one could separate the area planted with maize and the area harvested with maize, etc. For simplicity, I assume that they are equal and call it “area harvested maize” to make it clear that this area is relevant for calculating the maize production.

Dry Matter fraction of group 1 yield=

0.87

Units: Dmnl

This variable represents the dry matter share of maize yields. Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17.

effect factor of labor on yield=

0.8

Units: Dmnl

effect factor of nitrogen on yield=

4.03

Units: ha*Year/ton

4.03 This is a model specific constant being part of the Mitscherlich-Baule production function. It determines the strength of the reaction of maize yields to a change in nitrogen uptake. It was estimated on a data set from Zambia.

effect factor of water on yield=

0.004

Units: Year/mm

This is a model specific constant being part of the Mitscherlich-Baule production function. It determines the strength of the reaction of maize yields to a change in water uptake. It was estimated on a data set from Zambia.

effect intercept of soil organic matter on nitrogen=

reference nitrogen uptake share-initial relative soil organic matter*EFFECT slope of soil organic matter on nitrogen

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on nitrogen uptake.

effect of nitrogen on yield=

$1-10^{-(\text{effect factor of nitrogen on yield} \cdot \text{nitrogen uptake by group 1})}$

Units: Dmnl

This variable is an intermediate part of the Mitscherlich-Baule

production function.

effect of water on yield=

$$1-10^{(-\text{effect factor of water on yield}*\text{water plant uptake})}$$

Units: Dmnl

This variable is an intermediate part of the Mitscherlich-Baule production function.

effect slope of expenditure on plant residues removed=

$$-0.0015$$

Units: Year*ha/RLC

-0.0015

EFFECT slope of soil organic matter on nitrogen=

$$0.2$$

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on nitrogen uptake. The model reacts rather sensitive to this parameter. A reality check in simulation outcomes suggests a value lower than 0.2.

effect slope of soil organic matter on water=

$$0.1$$

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on water uptake. The model reacts rather sensitive to this parameter. A reality check in simulation outcomes suggests a value lower than 0.1.

group 1 yield=

$$\text{Yield plateau}*\text{effect of nitrogen on yield}*\text{effect of water on yield}$$

Units: ton/(ha*Year)

This variable represents average maize yields and is the result of the Mitscherlich-Baule production function (Schilling 2000, p.230). Note that the yields are determined using an operational approach: instead of factor application I use factor uptake.

indicated nitrogen uptake share=

$$\text{EFFECT slope of soil organic matter on nitrogen}*\text{relative soil organic matter}$$

+effect intercept of soil organic matter on nitrogen

Units: Dmnl

This variable represents the indicated share of mineralized nitrogen that could be taken up by maize plants depending on the soil organic matter content. The effect of soil organic matter on nitrogen uptake is assumed to be linear. Despite the existence of this linkage, its formal nature is not yet well researched (Johnston et al., 2009, Soil Organic Matter: Its importance in Sustainable Agriculture and Carbon Dioxide Fluxes).

indicated water uptake share=

$$\text{relative soil organic matter}*\text{effect slope of soil organic matter on water}+$$

intercept of som effect on water

Units: Dmnl

This variable represents the indicated share of water that could be taken up by maize plants depending on the soil organic matter content. The effect of soil organic matter on water uptake is assumed to be linear. Despite the existence of this linkage, its formal nature is not yet well researched (Johnston et al., 2009, Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes).

initial relative soil organic matter= INITIAL(

$$\text{relative soil organic matter})$$

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on nitrogen and water uptake.

intercept of som effect on water=

$$\text{reference water uptake share}-\text{initial relative soil organic matter}*\text{effect slope of soil organic matter on}$$

water

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on water uptake.

KG PER TON=
1000

Units: kg/ton

This variable represents the number of kilograms per metric ton
(1000).

max total n in plant residues reality check=

(1-minimal share of n going to yield)*nitrogen uptake by group 1

Units: ton/(ha*Year)

This variable represents the maximal amount of nitrogen in plant residues and is used to avoid extreme condition problems. It could happen (when the yields get very low) that there is more n in the plant residues than was taken up by the plant. This would violate the law of mass balance and therefore be totally unrealistic.

maximum nitrogen uptake share=

0.85

Units: Dmnl

This variable represents the maximum share of mineralised nitrogen that is taken up by maize plants. Schilling (2000). Pflanzenernährung und Düngug. p.435: Nährelementausnutzung bei Mineraldüngern (%). N:65-85%

maximum water uptake share=

0.5

Units: Dmnl

This variable represents the maximum share of water that is taken up by maize plants.

mineralised nitrogen=

nitrogen fertilizer application per hectare group 1+soil organic nitrogen mineralisation rate

Units: ton/(Year*ha)

This variable represents the amount of mineralized nitrogen from organic and inorganic sources (on average per hectare per year).

minimal share of n going to yield=

0.1

Units: Dmnl

This variable represents the minimal share of nitrogen going to yield and therefore is not available in the plant residues.

minimum nitrogen uptake share=

0.45

Units: Dmnl

This variable represents the minimum share of mineralised nitrogen that is taken up by maize plants. Schilling (2000). Pflanzenernährung und Düngug. p.435: Nährelementausnutzung bei Mineraldüngern (%). N:65-85%

minimum water uptake share=

0.05

Units: Dmnl

This variable represents the minimum share of water that is taken up by maize plants.

Nitrogen content of above ground residues=

0.006

Units: Dmnl

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Capter 11. Table 11.2. Page 11.17.

Nitrogen content of below ground residues=

0.007

Units: Dmnl

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Capter 11. Table 11.2. Page 11.17.

nitrogen fertilizer application=

(total nitrogen fertilizer expenditure real)/(nitrogen fertilizer price real

*KG PER TON)

Units: ton/Year

This variable represents the annual total nitrogen fertilizer application.

nitrogen fertilizer application per hectare group 1=

nitrogen fertilizer applied to group 1/AREA HARVESTED group 1 per farm

Units: ton/(Year*ha)

This variable represents the average per hectare annual nitrogen fertilizer application on maize field.

nitrogen fertilizer applied to group 1=

nitrogen fertilizer application*share of nitrogen to group 1

Units: ton/Year

This variable represents the total annual nitrogen fertilizer application to maize.

nitrogen fertilizer price real=

1.82

Units: RLC/kg

AVG 1984-2012 calculated from Data: 615

nitrogen in plant residues below ground=

plant residue below ground dry matter group 1*Nitrogen content of below ground residues

Units: ton/(Year*ha)

This variable represents the total amount of nitrogen in below ground plant residues.

nitrogen in plant residues above ground=

Plant Residue Above Ground Dry Matter*Nitrogen content of above ground residues

Units: ton/(Year*ha)

This variable represents the total amount of nitrogen in above ground plant residues.

nitrogen uptake by group 1=

mineralized nitrogen*uptake share of nitrogen

Units: ton/(Year*ha)

This variable represents the average amount of nitrogen that is taken up by maize plants on one hectare throughout one growing season.

per hectare expenditure for soil improvement=

soil improvement expenditure real/total planted area

Units: RLC/(Year*ha)

Plant Residue Above Ground Dry Matter=

Plant Residue Above Ground Intercept Plant Residue Above Ground Slope*yield group 1 dry matter

Units: ton/(Year*ha)

This variable represents the amount of residue dry matter production above ground (excluding yield). Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17. Note: units are Mg = Mega grams = 10^6 g = 1t

Plant Residue Above Ground Intercept=

0.61

Units: ton/(Year*ha)

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-19%

Plant Residue Above Ground Slope=

1.03

Units: Dmnl

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-3%

plant residue below ground dry matter group 1=

Above Ground Dry Matter group 1*Ration below ground residue to above ground dry matter

Units: ton/(Year*ha)

This variable represents the total amount of dry matter production below ground (assumed that all is left in the soil as residues). Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Page 11.14. From Description: $R=BGR/Yield=R(bio)*(AGR+Yield)/Yield \rightarrow BGR=(AGR+Yield)*R(bio)=Above\ Ground\ Dry\ Matter * R(bio)$

plant uptake share of water=

$Min(max(indicated\ water\ uptake\ share, minimum\ water\ uptake\ share), maximum\ water\ uptake\ share)$

Units: Dmnl

This variable represents the average share of water that is taken up by maize plants.

precipitation= WITH LOOKUP (

Time,

$[(2015,400)-(2025,900)],(2015,879),(2016,879),(2017,879),(2018,879),(2019,879),(2020,879),(2021,879),(2022,879),(2023,879),(2024,879),(2025,879))$

Units: mm/Year

AVG 1984-2013 calculated from data: 879

Ration below ground residue to above ground dry matter=

0.22

Units: Dmnl

Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-26%

reference nitrogen uptake share=

0.5

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on nitrogen uptake.

reference share of above ground plant residues removed from the field=

0.7

Units: Dmnl

reference water uptake share=

0.1

Units: Dmnl

This variable is used to formulate the effect strength of soil organic matter on water uptake.

relative available labor=

$relative\ household\ total\ labor*relative\ hired\ labor$

Units: Dmnl

relative available labor per hectare=

$relative\ available\ labor/AREA\ HARVESTED\ group\ 1\ per\ farm$

Units: Dmnl/ha

relative soil organic matter=

$soil\ organic\ matter/initial\ soil\ organic\ matter$

Units: Dmnl

This variable represents the organic dry matter amount relative to its initial value.

Share Group 1=

$SMOOTH\ N((indicated\ share\ of\ group\ 1\ from\ food\ supply\ group\ 1*0.6)+(indicated\ share\ of\ group\ 1\ from\ labor\ availability*0.1)+(indicated\ share\ of\ group\ 1\ from\ profit*0.2)+(indicated\ share\ of\ group\ 1\ from\ total\ planted\ area*0.1),6,(indicated\ share\ of\ group\ 1\ from\ food\ supply\ group\ 1*0.6)+(indicated\ share\ of\ group\ 1\ from\ labor\ availability*0.1)+(indicated\ share\ of\ group\ 1\ from\ profit*0.3)+(indicated\ share\ of\ group\ 1\ from\ total\ planted\ area*0.1),3)$

Units: Dmnl

share of above ground plant residues removed from the field=

$\max(\text{Min}(\text{reference share of above ground plant residues removed from the field} + \text{effect slope of expenditure on plant residues removed} * \text{per hectare expenditure for soil improvement}, 1), 0)$

Units: Dmnl

This variable represents share of above ground plant residues that are removed from the field, either for animal feeding, through burning or for other uses.

share of nitrogen to group 1 =

0.77

Units: Dmnl

This variable represents the share of total annual nitrogen fertilizer application going to maize.

soil improvement expenditure real =

farm expenditure for fertilizer and soil improvement * share of agricultural expenditure to soil improvement

Units: RLC/Year

soil organic nitrogen mineralization rate =

Soil Organic Nitrogen / average mineralization time

Units: ton/(Year*ha)

This variable represents the annual amount of nitrogen being mineralized from soil organic sources (per hectare).

total nitrogen fertilizer expenditure real =

total fertilizer expenditures real * share of fertilizer expenditure on nitrogen

Units: RLC/Year

This variable represents the annual amount of total fertilizer expenditures going to nitrogen (in real local currency).

total nitrogen in plant residues =

Min(total Nitrogen in plant residues IPCC, max total n in plant residues reality check)

Units: ton/(ha*Year)

This variable represents the total amount of nitrogen in plant residues and is used to avoid extreme condition problems. It could happen (when the yields get very low) that there is more n in the plant residues than was taken up by the plant. This would violate the law of mass balance and therefore be totally unrealistic.

total Nitrogen in plant residues IPCC =

nitrogen in plant residues below ground + nitrogen in plant residues above ground

Units: ton/(Year*ha)

This variable represents the total amount of nitrogen in plant residues left on the field after harvest.

total nitrogen in plant residues left on the field group 1 =

Min(total nitrogen in plant residues,

nitrogen in plant residues below ground + nitrogen in plant residues above ground

*(1 - share of above ground plant residues removed from the field))

Units: ton/(Year*ha)

This variable represents the actual total amount of nitrogen in plant residues left on the field after harvest (robust to extreme conditions failures).

total planted area = INTEG (

increase of field - ABANDON FIELDS, initial planted area)

Units: ha

uptake share of nitrogen =

Min(max(indicated nitrogen uptake share, minimum nitrogen uptake share),

maximum nitrogen uptake share)

Units: Dmnl

This variable represents the average share of mineralised nitrogen that is taken up by maize plants. Schilling (2000). Pflanzenernährung und Düngung. p.435: Nährelementausnutzung bei Mineraldüngern (%). N:65-85%

water plant uptake =

precipitation * plant uptake share of water

Units: mm/Year

This variable represents the average amount of water that is taken up by maize plants on one hectare throughout one growing season.

yield group 1 dry matter=

group 1 yield*Dry Matter fraction of group 1 yield

Units: ton/(Year*ha)

This variable represents the amount of dry matter in maize yields.

Yield plateau=

6.8

Units: ton/(ha*Year)

This variable is part of the Mitscherlich-Baule production function representing the maize yield under perfect factor availability.

A.2.2. Sector: Yield Group 2

Above Ground Dry Matter group 2=

Plant Residue Above Ground Dry Matter group 2+yield group 2 dry matter

Units: ton/(Year*ha)

AREA HARVESTED group 2 per farm=

total planted area*Share Group 2

Units: ha

carbon to nitrogen ratio 0=

soil organic carbon 0/Soil Organic Nitrogen 0

Units: Dmnl

Dry Matter fraction of group 2=

0.565

Units: Dmnl

effect factor of nitrogen on yield group 2=

3.303

Units: ha*Year/ton

effect factor of water on yield group 2=

0.006

Units: Year/mm

effect intercept of soil organic matter on nitrogen 0=

reference nitrogen uptake share 0-initial relative soil organic matter 0*EFFECT slope of soil organic matter on nitrogen 0

Units: Dmnl

effect of nitrogen on group 2 yield=

$1-10^{(-\text{effect factor of nitrogen on yield group 2}*\text{nitrogen uptake by group 2})}$

Units: Dmnl

effect of water on group 2 yield=

$1-10^{(-\text{effect factor of water on yield group 2}*\text{water plant uptake 0})}$

Units: Dmnl

effect slope of expenditure on plant residues removed 0=

-0.0015

Units: Year*ha/RLC

EFFECT slope of soil organic matter on nitrogen 0=

0.2

Units: Dmnl

effect slope of soil organic matter on water 0=

0.1

Units: Dmnl

group 1 yield=

Yield plateau*effect of nitrogen on yield*effect of water on yield

Units: ton/(ha*Year)

group 2 yield=

Yield plateau group 2*effect of nitrogen on group 2 yield*effect of water on group 2 yield

Units: ton/(ha*Year)

indicated nitrogen uptake share 0=

EFFECT slope of soil organic matter on nitrogen 0*relative soil organic matter 0

+effect intercept of soil organic matter on nitrogen 0

Units: Dmnl

indicated water uptake share 0=

relative soil organic matter 0*effect slope of soil organic matter on water 0

+intercept of som effect on water 0

Units: Dmnl

initial relative soil organic matter 0= INITIAL(

relative soil organic matter 0)

Units: Dmnl

intercept of som effect on water 0=

reference water uptake share 0-initial relative soil organic matter 0*effect slope of soil organic matter

on water 0

Units: Dmnl

KG PER TON=

1000

Units: kg/ton

max total n in plant residues reality check 0=

(1-minimal share of n going to yield 0)*nitrogen uptake by group 2

Units: ton/(ha*Year)

maximum nitrogen uptake share 0=

0.53

Units: Dmnl

maximum water uptake share 0=

0.6

Units: Dmnl

mineralised nitrogen group 2 field=

nitrogen fertilizer application per hectare group 2+soil organic nitrogen mineralisation rate 0

Units: ton/(Year*ha)

minimal share of n going to yield 0=

0.1

Units: Dmnl

minimum nitrogen uptake share 0=

0.08

Units: Dmnl

minimum water uptake share 0=
0.05

Units: Dmnl

Nitrogen content of above ground residues group 2=
0.013

Units: Dmnl

Nitrogen content of below ground residues group 2=
0.022

Units: Dmnl

nitrogen fertilizer application 0=
(total nitrogen fertilizer expenditure real)/(nitrogen fertilizer price real
*KG PER TON)

Units: ton/Year

nitrogen fertilizer application per hectare group 2=
nitrogen fertilizer applied to group 2/AREA HARVESTED group 2 per farm

Units: ton/(Year*ha)

nitrogen fertilizer applied to group 2=
nitrogen fertilizer application 0*share of nitrogen to group 2

Units: ton/Year

nitrogen fertilizer price real=
1.82

Units: RLC/kg

nitrogen in plant residues below ground group 2=
plant residue below ground dry matter group 2*Nitrogen content of below ground residues group 2

Units: ton/(Year*ha)

nitrogen in plant residues above ground group 2=
Plant Residue Above Ground Dry Matter group 2*Nitrogen content of above ground residues group 2

Units: ton/(Year*ha)

nitrogen uptake by group 2=
mineralised nitrogen group 2 field*uptake share of nitrogen 0

Units: ton/(Year*ha)

per hectare expenditure for soil improvement 0=
soil improvement expenditure real/total planted area

Units: RLC/(Year*ha)

Plant Residue Above Ground Dry Matter group 2=
Plant Residue Above Ground Intercept group 2+Plant Residue Above Ground Slope group 2
*yield group 2 dry matter

Units: ton/(Year*ha)

Plant Residue Above Ground Intercept group 2=
0.955

Units: ton/(Year*ha)

Plant Residue Above Ground Slope group 2=
0.62

Units: Dmnl

plant residue below ground dry matter group 2=

Above Ground Dry Matter group 2*Ration below ground residue to above ground dry matter 0
Units: ton/(Year*ha)

plant uptake share of water 0=
Min(max(indicated water uptake share 0,minimum water uptake share 0),maximum water uptake share 0)
Units: Dmnl

precipitation= WITH LOOKUP (
Time,
((2015,400)-(2025,900)],(2015,879),(2016,879),(2017,879),(2018,879),(2019,879),(2020,879),(2021,879),(2022,879),(2023,879),(2024,879),(2025,879))
Units: mm/Year

Ration below ground residue to above ground dry matter 0=
0.22
Units: Dmnl

reference nitrogen uptake share 0=
0.5
Units: Dmnl

reference share of above ground plant residues removed from the field 0=
0.7
Units: Dmnl

reference water uptake share 0=
0.1
Units: Dmnl

relative soil organic matter 0=
soil organic matter 0/initial soil organic matter 0
Units: Dmnl

Share Group 2=
((indicated share of group 2 from gender*0.075)+(indicated share of group 2 from farm income *0.2)+(indicated share of group 2 from total planted area+0.025)+(indicated share of group 2 from food supply group 2*0.4)+(indicated share of group 2 from profit *0.3))*indicated share of group 2 from share of group 1
Units: Dmnl

share of above ground plant residues removed from the field 0=
max(Min(reference share of above ground plant residues removed from the field 0+effect slope of expenditure on plant residues removed 0*per hectare expenditure for soil improvement 0,1),0)
Units: Dmnl

share of nitrogen to group 2=
0.11
Units: Dmnl

soil improvement expenditure real=
farm expenditure for fertilizer and soil improvement*share of agricultural expenditure to soil improvement
Units: RLC/Year

soil organic nitrogen mineralisation rate 0=
Soil Organic Nitrogen 0/average mineralization time 0
Units: ton/(Year*ha)

total nitrogen fertilizer expenditure real=
total fertilizer expenditures real*share of fertilizer expenditure on nitrogen
Units: RLC/Year

total nitrogen in plant residues 0=
Min(total Nitrogen in plant residues IPCC 0,max total n in plant residues reality check 0)
Units: ton/(ha*Year)

total Nitrogen in plant residues IPCC 0=
nitrogen in plant residues below ground group 2+nitrogen in plant residues above ground group 2
Units: ton/(Year*ha)

total nitrogen in plant residues left on the field group 2=
Min(total nitrogen in plant residues 0, nitrogen in plant residues below ground group 2+nitrogen in
plant residues above ground group 2*(1-share of above ground plant residues removed from the field 0))
Units: ton/(Year*ha)

total planted area= INTEG (
increase of field-ABANDON FIELDS,
initial planted area)
Units: ha

uptake share of nitrogen 0=
Min(max(indicated nitrogen uptake share 0,minimum nitrogen uptake share 0),maximum nitrogen
uptake share 0)
Units: Dmnl

water plant uptake 0=
precipitation*plant uptake share of water 0
Units: mm/Year

yield group 2 dry matter=
group 2 yield*Dry Matter fraction of group 2
Units: ton/(Year*ha)

Yield plateau group 2=
9
Units: ton/(ha*Year)

A.2.3. Sector: Yield Group 3

Above Ground Dry Matter 1=
Plant Residue Above Ground Dry Matter 0+yield group 3 dry matter
Units: ton/(Year*ha)

AREA HARVESTED group 3 per farm=
total planted area*Share Group 3
Units: ha

Dry Matter fraction of group 3 yield 0=
0.9
Units: Dmnl

effect factor of nitrogen on yield 1=
4.503
Units: ha*Year/ton

effect factor of water on yield 1=
0.004
Units: Year/mm

effect intercept of soil organic matter on nitrogen 1=
reference nitrogen uptake share 1-initial relative soil organic matter 1*EFFECT slope of soil organic matter on nitrogen 1
Units: Dmnl

effect of nitrogen on yield 1=
 $1-10^{(-\text{effect factor of nitrogen on yield 1}*\text{nitrogen uptake by group 1 1})}$
Units: Dmnl

effect of water on yield 1=
 $1-10^{(-\text{effect factor of water on yield 1}*\text{water plant uptake 1})}$
Units: Dmnl

effect slope of expenditure on plant residues removed 1=
-0.0015
Units: Year*ha/RLC

EFFECT slope of soil organic matter on nitrogen 1=
0.2
Units: Dmnl

effect slope of soil organic matter on water 1=
0.1
Units: Dmnl

group 3 yield=
Yield plateau group 3*effect of nitrogen on yield 1*effect of water on yield 1
Units: ton/(ha*Year)

indicated nitrogen uptake share 1=
EFFECT slope of soil organic matter on nitrogen 1*relative soil organic matter group 3 field
+effect intercept of soil organic matter on nitrogen 1
Units: Dmnl

indicated water uptake share 1=
relative soil organic matter group 3 field*effect slope of soil organic matter on water 1
+intercept of som effect on water 1
Units: Dmnl

initial relative soil organic matter 1= INITIAL(
relative soil organic matter group 3 field)
Units: Dmnl

intercept of som effect on water 1=
reference water uptake share 1-initial relative soil organic matter 1*effect slope of soil organic matter on water 1
Units: Dmnl

KG PER TON=
1000
Units: kg/ton

max total n in plant residues reality check 1=
(1-minimal share of n going to yield 1)*nitrogen uptake by group 1 1
Units: ton/(ha*Year)

maximum nitrogen uptake share 1=
0.85
Units: Dmnl

maximum water uptake share 1=
0.8

Units: Dmnl

mineralised nitrogen 1=

nitrogen fertilizer application per hectare maize 0+soil organic nitrogen mineralisation rate

Units: ton/(Year*ha)

minimal share of n going to yield 1=

0.1

Units: Dmnl

minimum nitrogen uptake share 1=

0.45

Units: Dmnl

minimum water uptake share 1=

0.1

Units: Dmnl

Nitrogen content of above ground residues 0=

0.015

Units: Dmnl

Nitrogen content of below ground residues 0=

0.007

Units: Dmnl

nitrogen fertilizer application per hectare maize 0=

nitrogen fertilizer applied to group 3/AREA HARVESTED group 3 per farm

Units: ton/(Year*ha)

nitrogen fertilizer application to group 3=

(total nitrogen fertilizer expenditure real)/(nitrogen fertilizer price real

*KG PER TON)

Units: ton/Year

nitrogen fertilizer applied to group 3=

nitrogen fertilizer application to group 3*share of nitrogen to group 3

Units: ton/Year

nitrogen fertilizer price real=

1.82

Units: RLC/kg

nitrogen in plant residues below ground 1=

plant residue below ground dry matter 1*Nitrogen content of below ground residues 0

Units: ton/(Year*ha)

nitrogen in plant residues above ground 0=

Plant Residue Above Ground Dry Matter 0*Nitrogen content of above ground residues 0

Units: ton/(Year*ha)

nitrogen uptake by group 1 1=

mineralised nitrogen 1*uptake share of nitrogen 1

Units: ton/(Year*ha)

per hectare expenditure for soil improvement 1=

soil improvement expenditure real/total planted area

Units: RLC/(Year*ha)

Plant Residue Above Ground Dry Matter 0=

Plant Residue Above Ground Intercept 0+Plant Residue Above Ground Slope 0*
yield group 3 dry matter

Units: ton/(Year*ha)

Plant Residue Above Ground Intercept 0=

0

Units: ton/(Year*ha)

Plant Residue Above Ground Slope 0=

0.18

Units: Dmnl

plant residue below ground dry matter 1=

Above Ground Dry Matter 1*Ration below ground residue to above ground dry matter 1

Units: ton/(Year*ha)

plant uptake share of water 1=

Min(max(indicated water uptake share 1,minimum water uptake share 1),maximum water uptake share
1)

Units: Dmnl

precipitation= WITH LOOKUP (

Time,

((2015,400)-(2025,900)],(2015,879),(2016,879),(2017,879),(2018,879),(2019,
,879),(2020,879),(2021,879),(2022,879),(2023,879),(2024,879),(2025,879))

Units: mm/Year

Ration below ground residue to above ground dry matter 1=

0.54

Units: Dmnl

reference nitrogen uptake share 1=

0.5

Units: Dmnl

reference share of above ground plant residues removed from the field 1=

0.7

Units: Dmnl

reference water uptake share 1=

0.1

Units: Dmnl

relative soil organic matter group 3 field=

soil organic matter 0 0/initial soil organic matter 0 0

Units: Dmnl

share of above ground plant residues removed from the field 1=

max(Min(reference share of above ground plant residues removed from the field 1+effect slope of
expenditure on plant residues removed 1*per hectare expenditure for soil improvment 1
,1),0)

Units: Dmnl

share of nitrogen to group 3=

0.12

Units: Dmnl

soil improvement expenditure real=
 farm expenditure for fertilizer and soil improvement*share of agricultural expenditure to soil improvement
 Units: RLC/Year

soil organic nitrogen mineralisation rate=
 Soil Organic Nitrogen/average mineralization time
 Units: ton/(Year*ha)

total nitrogen fertilizer expenditure real=
 total fertilizer expenditures real*share of fertilizer expenditure on nitrogen
 Units: RLC/Year

total nitrogen in plant residues 1=
 Min(total Nitrogen in plant residues IPCC 1,max total n in plant residues reality check 1)
 Units: ton/(ha*Year)

total Nitrogen in plant residues IPCC 1=
 nitrogen in plant resdiues below ground 1+nitrogen in plant residues above ground 0
 Units: ton/(Year*ha)

total nitrogen in plant residues left on the field group 3=
 Min(total nitrogen in plant residues 1,nitrogen in plant resdiues below ground 1+nitrogen in plant residues above ground 0*(1-share of above ground plant residues removed from the field 1))
 Units: ton/(Year*ha)

total planted area= INTEG (
 increasement of field-ABANDON FIELDS,nitial planted area)
 Units: ha

uptake share of nitrogen 1=
 Min(max(indicated nitrogen uptake share 1,minimum nitrogen uptake share 1),maximum nitrogen uptake share 1)
 Units: Dmnl

water plant uptake 1=
 precipitation*plant uptake share of water 1
 Units: mm/Year

yield group 3 dry matter=
 group 3 yield*Dry Matter fraction of group 3 yield 0
 Units: ton/(Year*ha)

Yield plateau group 3=
 3
 Units: ton/(ha*Year)

A.2.4. Sector: Soil Organic Matter Group 1

animal carbon per hectare=
 animal organic matter per hectare*carbon share in dry matter
 Units: ton/(ha*Year)
 This variable represents the annual amount of organic carbon applied per hectare arable land through animal manure.

animal organic matter per hectare=
 0.09
 Units: ton/(ha*Year)

This variable represents the annual amount of organic matter applied per hectare arable land through animal manure.

animal organic nitrogen per hectare=
0.0085

Units: ton/(Year*ha)

This variable represents the annual amount of organic nitrogen applied per hectare arable land through animal manure.

average mineralization time=
31

Units: Year

This constant represents the average soil stock residence time for carbon and nitrogen. It is influenced by: Soil Moisture, Temperature, Clay Content, pH, N Availability. See: Scheffer and Schachtschabel (2010). Lehrbuch der Bodenkunde. Largest Part of SOM: AVG min time = 10-50years, Page 73.

carbon in plant residues remaining on the field=
plant residues remaining on the field*carbon share in dry matter

Units: ton/(ha*Year)

This variable represents the total amount of carbon contained in plant residues remaining on the field.

carbon share in dry matter=
0.58

Units: Dmnl

This variable represents the carbon share in total organic dry matter. Scheffer/Schachtschabel (2010): Lehrbuch der Bodenkunde. p. 55. Schubert (2011). Pflanzenernährung. Grundwissen Bachelor. Ulmer UTB. p153: "Bei der Umrechnung des C-Gehaltes in organische Substanz kann eine mittlere C-Konzentration der organischen Substanz von 58% zugrunde gelegt werden. Da die C-Konzentrationen zwischen 40-60% schwanken können, kann der Umrechnungsfaktor 1.7-3.2 betragen."

carbon to nitrogen ratio=
soil organic carbon/Soil Organic Nitrogen

Units: Dmnl

This variable represents C to N ratio in soil organic matter.

initial soil organic carbon=
20

Units: ton/ha

Equation: eq init soc This constant represents the initial value of the soil organic carbon stock. original = 20 F4 = 15

initial soil organic matter= INITIAL(soil organic matter)

Units: ton/ha

This variable represents the initial per hectare amount of organic dry matter on arable land.

initial soil organic nitrogen=
1.6

Units: ton/ha

Equation: eq init son This constant represents the initial value the soil organic nitrogen stock. (original = 1.6)

nitrogen fixation through soil bacteria=
0.03

Units: ton/(ha*Year)

This flow represents N fixation through free living soil bacteria (excluding nodule bacteria from legumes) Scheffer/Schachtschabel p.402/403: normal input in europe 1-30 kgN ha-1a-1, in tropics up to 100 kgN ha-1a-1

Plant Residue Above Ground Dry Matter=

Plant Residue Above Ground Intercept+Plant Residue Above Ground Slope*yield group 1 dry matter

Units: ton/(Year*ha)

This variable represents the amount of residue dry matter production above ground (excluding yield). Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Table 11.2. Page 11.17. Note: units are Mg = Mega grams = 10^6 g = 1t

plant residue below ground dry matter group 1=

Above Ground Dry Matter group 1 * Ration below ground residue to above ground dry matter

Units: ton/(Year*ha)

This variable represents the total amount of dry matter production below ground (assumed that all is left in the soil as residues). Source: IPCC Guidelines for National Greenhouse Gas Inventories (2006). Chapter 11. Page 11.14. From Description: $R=BGR/Yield=R(bio)*(AGR+Yield)/Yield$
 $BGR=(AGR+Yield)*R(bio)=Above$
Ground Dry Matter * R(bio)

plant residues remaining on the field=

Plant Residue Above Ground Dry Matter*(1-share of above ground plant residues removed from the field)+plant residue below ground dry matter group 1

Units: ton/(ha*Year)

This variable represents the total amount of plant residues remaining on the field.

relative soil organic matter=

soil organic matter/initial soil organic matter

Units: Dmnl

This variable represents the organic dry matter amount relative to its initial value.

share of above ground plant residues removed from the field=

max(Min(reference share of above ground plant residues removed from the field+effect slope of expenditure on plant residues removed*per hectare expenditure for soil improvement,1),0)

Units: Dmnl

This variable represents share of above ground plant residues are removed from the field, either for animal feeding, through burning or for other uses.

soil organic carbon= INTEG (

soil organic carbon input-soil organic carbon mineralisation rate, initial soil organic carbon)

Units: ton/ha

This stock represents the level of total organic carbon in the soil of one hectare arable land of average quality.

soil organic carbon input=

carbon in plant residues remaining on the field+animal carbon per hectare

Units: ton/(Year*ha)

This variable represents the organic annual per hectare carbon input to the stock of soil organic nitrogen.

soil organic carbon mineralisation rate=

soil organic carbon/average mineralization time

Units: ton/(Year*ha)

This variable represents the annual amount of carbon being mineralised from soil organic sources (per hectare).

soil organic matter=

soil organic carbon/carbon share in dry matter

Units: ton/ha

This variable represents the per hectare amount of organic dry matter on arable land.

Soil Organic Nitrogen= INTEG (

nitrogen fixation through soil bacteria+soil organic nitrogen input-soil organic nitrogen mineralisation rate,initial soil organic nitrogen)

Units: ton/ha

This stock represents the level of total organic nitrogen in the soil of one hectare arable land of average quality.

soil organic nitrogen input=

animal organic nitrogen per hectare+total nitrogen in plant residues left on the field group 1

Units: ton/(ha*Year)

This variable represents the organic annual per hectare nitrogen input to the stock of soil organic nitrogen.

soil organic nitrogen mineralisation rate=

Soil Organic Nitrogen/average mineralization time

Units: ton/(Year*ha)

This variable represents the annual amount of nitrogen being mineralised from soil organic sources (per hectare).

total nitrogen in plant residues left on the field group 1=

Min(total nitrogen in plant residues, nitrogen in plant residues below ground+nitrogen in plant residues above ground*(1-share of above ground plant residues removed from the field))

Units: ton/(Year*ha)

This variable represents the actual total amount of nitrogen in plant residues left on the field after harvest (robust to conditions failures).

A.2.5. Sector: Soil Organic Matter Group 2

animal carbon per hectare 0=

animal organic matter per hectare 0*carbon share in dry matter 0

Units: ton/(ha*Year)

animal organic matter per hectare 0=

0.09

Units: ton/(ha*Year)

animal organic nitrogen per hectare 0=

0.0085

Units: ton/(Year*ha)

average mineralization time 0=

31

Units: Year

carbon in plant residues remaining on the field 0=

plant residues remaining on the field 0*carbon share in dry matter 0

Units: ton/(ha*Year)

carbon share in dry matter 0=

0.44

Units: Dmnl

carbon to nitrogen ratio 0=

soil organic carbon 0/Soil Organic Nitrogen 0

Units: Dmnl

initial soil organic carbon 0=

20

Units: ton/ha

initial soil organic matter 0= INITIAL(

soil organic matter 0)

Units: ton/ha

initial soil organic nitrogen 0=

1.6

Units: ton/ha

nitrogen fixation through soil bacteria 0=

0.1

Units: ton/(ha*Year)

Plant Residue Above Ground Dry Matter=

Plant Residue Above Ground Intercept+Plant Residue Above Ground Slope*yield group 1 dry matter
Units: ton/(Year*ha)

Plant Residue Above Ground Dry Matter group 2=

Plant Residue Above Ground Intercept group 2+Plant Residue Above Ground Slope group 2
*yield group 2 dry matter
Units: ton/(Year*ha)

plant residue below ground dry matter group 1=

Above Ground Dry Matter group 1*Ration below ground residue to above ground dry matter
Units: ton/(Year*ha)

plant residue below ground dry matter group 2=

Above Ground Dry Matter group 2*Ration below ground residue to above ground dry matter 0
Units: ton/(Year*ha)

plant residues remaining on the field 0=

Plant Residue Above Ground Dry Matter group 2*(1-share of above ground plant residues removed
from the field 0)+plant residue below ground dry matter group 2
Units: ton/(ha*Year)

relative soil organic matter 0=

soil organic matter 0/initial soil organic matter 0
Units: Dmnl

share of above ground plant residues removed from the field=

max(Min(reference share of above ground plant residues removed from the field+effect slope of
expenditure on plant residues removed*per hectare expenditure for soil improvement,1),0)
Units: Dmnl

share of above ground plant residues removed from the field 0=

max(Min(reference share of above ground plant residues removed from the field 0+effect slope of
expenditure on plant residues removed 0*per hectare expenditure for soil improvement 0,1),0)
Units: Dmnl

soil organic carbon 0= INTEG (

soil organic carbon input 0-soil organic carbon mineralisation rate 0,
initial soil organic carbon 0)

Units: ton/ha

soil organic carbon input 0=

carbon in plant residues remaining on the field 0+animal carbon per hectare 0
Units: ton/(Year*ha)

soil organic carbon mineralisation rate 0=

soil organic carbon 0/average mineralization time 0
Units: ton/(Year*ha)

soil organic matter 0=

soil organic carbon 0/carbon share in dry matter 0
Units: ton/ha

Soil Organic Nitrogen 0= INTEG (

nitrogen fixation through soil bacteria 0+soil organic nitrogen input 0-soil organic nitrogen
mineralisation rate 0,initial soil organic nitrogen 0)

Units: ton/ha

soil organic nitrogen input 0=

animal organic nitrogen per hectare 0+total nitrogen in plant residues left on the field group 2

Units: ton/(ha*Year)

soil organic nitrogen mineralisation rate 0=
Soil Organic Nitrogen 0/average mineralization time 0
Units: ton/(Year*ha)

total nitrogen in plant residues left on the field group 2=
Min(total nitrogen in plant residues 0nitrogen in plant residues below ground group 2+nitrogen in plant residues above ground group 2*(1-share of above ground plant residues removed from the field 0))
Units: ton/(Year*ha)

A.2.6. Sector: Soil Organic Matter Group 3

animal carbon per hectare 0 0=
animal organic matter per hectare 0 0*carbon share in dry matter 0 0
Units: ton/(ha*Year)

animal organic matter per hectare 0 0=
0.09
Units: ton/(ha*Year)

animal organic nitrogen per hectare 0 0=
0.0085
Units: ton/(Year*ha)

average mineralization time 0 0=
31
Units: Year

carbon in plant residues remaining on the field 0 0=
plant residues remaining on the group 3 field*carbon share in dry matter 0 0
Units: ton/(ha*Year)

carbon share in dry matter 0 0=
0.6
Units: Dmnl

carbon to nitrogen ratio 0 0=
soil organic carbon 0 0/Soil Organic Nitrogen 0 0
Units: Dmnl

initial soil organic carbon 0 0=
20
Units: ton/ha

initial soil organic matter 0 0= INITIAL(
soil organic matter 0 0)
Units: ton/ha

initial soil organic nitrogen 0 0=
1.2
Units: ton/ha

nitrogen fixation through soil bacteria 0 0=
0.03
Units: ton/(ha*Year)

Plant Residue Above Ground Dry Matter=
Plant Residue Above Ground Intercept+Plant Residue Above Ground Slope*yield group 1 dry matter

Units: ton/(Year*ha)

Plant Residue Above Ground Dry Matter 0=

Plant Residue Above Ground Intercept 0+Plant Residue Above Ground Slope 0*
yield group 3 dry matter

Units: ton/(Year*ha)

plant residue below ground dry matter 1=

Above Ground Dry Matter 1*Ration below ground residue to above ground dry matter 1

Units: ton/(Year*ha)

plant residue below ground dry matter group 1=

Above Ground Dry Matter group 1*Ration below ground residue to above ground dry matter

Units: ton/(Year*ha)

plant residues remaining on the group 3 field=

Plant Residue Above Ground Dry Matter 0*(1-share of above ground plant residues removed from the
field 1)+plant residue below ground dry matter 1

Units: ton/(ha*Year)

relative soil organic matter group 3 field=

soil organic matter 0 0/initial soil organic matter 0 0

Units: Dmnl

share of above ground plant residues removed from the field=

max(Min(reference share of above ground plant residues removed from the field+effect slope of
expenditure on plant residues removed*per hectare expenditure for soil improvement,1),0)

Units: Dmnl

share of above ground plant residues removed from the field 1=

max(Min(reference share of above ground plant residues removed from the field 1
+effect slope of expenditure on plant residues removed 1*per hectare expenditure for soil improvement 1,1),0)

Units: Dmnl

soil organic carbon 0 0= INTEG (

soil organic carbon input 0 0-soil organic carbon mineralisation rate 0 0,initial soil organic carbon 0 0)

Units: ton/ha

soil organic carbon input 0 0=

carbon in plant residues remaining on the field 0 0+animal carbon per hectare 0 0

Units: ton/(Year*ha)

soil organic carbon mineralisation rate 0 0=

soil organic carbon 0 0/average mineralization time 0 0

Units: ton/(Year*ha)

soil organic matter 0 0=

soil organic carbon 0 0/carbon share in dry matter 0 0

Units: ton/ha

Soil Organic Nitrogen 0 0= INTEG (

nitrogen fixation through soil bacteria 0 0+soil organic nitrogen input 0 0
-soil organic nitrogen mineralisation rate 0 0,

initial soil organic nitrogen 0 0)

Units: ton/ha

soil organic nitrogen input 0 0=

animal organic nitrogen per hectare 0 0+total nitrogen in plant residues left on the field group 3

Units: ton/(ha*Year)

soil organic nitrogen mineralisation rate $0.0 = \frac{\text{Soil Organic Nitrogen}}{\text{average mineralization time}}$
 Units: ton/(Year*ha)

total nitrogen in plant residues left on the field $\text{group 3} = \text{Min}(\text{total nitrogen in plant residues}, \text{nitrogen in plant residues below ground}) + \text{nitrogen in plant residues above ground} * (1 - \text{share of above ground plant residues removed from the field})$
 Units: ton/(Year*ha)

A.2.7. Sector: Supply and Demand- Group 1

AREA HARVESTED group 1 per farm =
 $\text{total planted area} * \text{Share Group 1}$
 Units: ha

This variable represents the area on which maize is produced. that one could separate the area planted with maize and the area harvested with maize, etc. For simplicity I assume that they are equal and call it “area harvested maize” to make it clear that this area is relevant for calculating the maize production.

Average Dietary Energy Requirement =
 2200
 Units: kcal/(person*day)

This variable represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organisation of the United Nations (FAO) that calculate this parameter dependent on several population characteristics (e.g. age structure, level of physical activity, etc.). While the FAO value slightly changes over time, for simplicity, I assume a constant value of 2200 being realistic for the Sub-Saharan Africa region.

days per year =
 365
 Units: day/Year
 This variable represents the number of days per year (365).

energy share of group 1 on total diet =
 0.5
 Units: Dmnl

0.5 This variable represents the intended share of kilocalories coming from maize compared to the total diet. In Sub-Saharan African countries where maize is the staple crop this share is typically high (40%-70%).

group 1 for non food use =
 $\text{group 1 for seed use} + (\text{Share of group 1 production to animal fodder} + \text{share of group 1 production waste})$
 Units: ton/Year
 This variable represents the annual maize demand for non-food purposes including seed, animal fodder and food waste.

group 1 for seed use =
 $\text{AREA HARVESTED group 1 per farm} * \text{seed per hectare}$
 Units: ton/Year
 This variable represents the annual amount of maize used as seeds planting the fields.

group 1 production per farm =
 $\text{AREA HARVESTED group 1 per farm} * \text{group 1 yield}$
 Units: ton/Year

group 1 yield =
 $\text{Yield plateau} * \text{effect of nitrogen on yield} * \text{effect of water on yield}$
 Units: ton/(ha*Year)

This variable represents average maize yields and is the result of the Mitscherlich-Baule production function (Schilling 2000, p.230). Note that the yields are determined using an operational approach: instead of factor application I use factor uptake.

household group 1 demand=
group 1 for non food use+indicated total group 1 consumption
Units: ton/Year

Household Group 1 Inventory= INTEG (
group 1 production per farm-sales group 1, initial maize inventory)
Units: ton

indicated total calory consumption=
SIZE OF THE HOUSEHOLD*Average Dietary Energy Requirement*days per year
Units: kcal/Year
This variable represents the indicated annual total food consumption of the total population in kilocalories.

indicated total group 1 consumption=
indicated total calory consumption*energy share of group 1 on total diet/(
kcal per kg group 1*KG PER TON)
Units: ton/Year

initial maize inventory=
1.5
Units: ton

kcal per kg group 1=
3071
Units: kcal/kg
This variable represents the number of kilocalories per kilogram maize. It is estimated from FAO data.

KG PER TON=
1000
Units: kg/ton
This variable represents the number of kilograms per metric ton (1000).

sales group 1=
group 1 production per farm*share of group 1 production sold
Units: ton/Year

seed per hectare=
0.03
Units: ton/(ha*Year)
This constant represents the amount of seed maize used to plant one average hectare.

Share Group 1=
SMOOTH N((indicated share of group 1 from food supply group 1*0.6)+(indicated share of group 1
from labor availability*0.1)+(indicated share of group 1 from profit*0.2)+(indicated share of group 1 from total
planted area*0.1),6,(indicated share of group 1 from food supply group 1*0.6)+(indicated share of group 1 from
labor availability*0.1)+(indicated share of group 1 from profit*0.3)+(indicated share of group 1 from total
planted area*0.1),3)
Units: Dmnl

share of group 1 production sold=
Min(indicated share of production sold from group 1 profitability*relative weight of profitability in
sales decision+indicated share of production sold from group 1 availability*(1-relative weight of profitability in
sales decision), 1)
Units: Dmnl

Share of group 1 production to animal fodder=
0.02
Units: Dmnl
This constant represents the share of total annual maize supply used to feed animals.

share of group 1 production waste=
0.033

Units: Dmnl

This constant represents the share of total annual maize supply being lost and wasted.

SIZE OF THE HOUSEHOLD= INTEG (
(household births-household deaths),initial Size of The Household)

Units: person

total planted area= INTEG (
increase of field-ABANDON FIELDS, initial planted area)

Units: ha

A.2.8. Sector: Supply and Demand- Group 2

AREA HARVESTED group 2 per farm=
total planted area*Share Group 2

Units: ha

Average Dietary Energy Requirement=
2200

Units: kcal/(person*day)

days per year=
365

Units: day/Year

energy share of group 2 on total diet=
0.25

Units: Dmnl

group 1 for seed use 0=
AREA HARVESTED group 2 per farm*seed per hectare 0

Units: ton/Year

group 2 for non food use=
group 1 for seed use 0+(Share of group 2 production to animal fodder+share of group 2 production waste)

Units: ton/Year

group 2 production per farm=
AREA HARVESTED group 2 per farm*group 2 yield

Units: ton/Year

group 2 yield=
Yield plateau group 2*effect of nitrogen on group 2 yield*effect of water on group 2 yield

Units: ton/(ha*Year)

household group 2 demand=
group 2 for non food use+indicated total group 1 consumption 0

Units: ton/Year

Household Group 2 Inventory= INTEG (
group 2 production per farm-sales group 2,initial maize inventory 0)

Units: ton

indicated total calory consumption 0=
SIZE OF THE HOUSEHOLD*Average Dietary Energy Requirement*days per year

Units: kcal/Year

indicated total group 1 consumption 0=
indicated total calory consumption 0*energy share of group 2 on total diet/(kcal per kg group 2*KG
PER TON)
Units: ton/Year

initial maize inventory 0=
1.5
Units: ton

kcal per kg group 2=
2400
Units: kcal/kg

KG PER TON=
1000
Units: kg/ton

sales group 1=
group 1 production per farm*share of group 1 production sold
Units: ton/Year

sales group 2=
group 2 production per farm*share of group 2 production sold
Units: ton/Year

seed per hectare 0=
0.02
Units: ton/(ha*Year)

Share Group 2=
((indicated share of group 2 from gender*0.075)+(indicated share of group 2 from farm income
*0.2)+(indicated share of group 2 from total planted area+0.025)+(indicated share of group 2 from food supply
group 2*0.4)+(indicated share of group 2 from profit*0.3))*indicated share of group 2 from share of group 1
Units: Dmnl

share of group 1 production sold=
Min(indicated share of production sold from group 1 profitability*relative weight of profitability in
sales decision+indicated share of production sold from group 1 availability*(1-relative weight of profitability in
sales decision), 1)
Units: Dmnl

Share of group 2 production to animal fodder=
0.005
Units: Dmnl

share of group 2 production waste=
0.023
Units: Dmnl

SIZE OF THE HOUSEHOLD= INTEG (
(household births-household deaths), initial Size of The Household)
Units: person

total planted area= INTEG (
increasement of field-ABANDON FIELDS,initial planted area)
Units: ha

A.2.9. Sector: Farm Decisions – Group 1

aggregated farm income real= INTEG (
change of aggregated farm income,
1000)

Units: RLC/Year

AREA HARVESTED group 1 per farm=
total planted area*Share Group 1

Units: ha

This variable represents the area on which maize is produced. Note that one could separate the area planted with maize and the area harvested with maize, etc. For simplicity I assume that they are equal and call it "area harvested maize" to make it clear that this area is relevant for calculating the maize production.

availability of food in kcal per capita per day=
per capita food availability kcal per year/days per year

Units: kcal/(person*day)

This variable represents the number of total kilocalories from maize products that are on average available per person per day.

availability per capita per day kcal group 1=
per capita kcal group 1/days per year

Units: kcal/(person*day)

"average household non-agriculture income"=
300

Units: RLC/Year

"average household off-farm income"= WITH LOOKUP (
Time,

[(2015,400)-(2025,800)],(2015,453.5),(2016,483.75),(2017,514),(2018,544.25
,(2019,574.5),(2020,604.75),(2021,635),(2022,665.25),(2023,695.5),(2024,725.75
,(2025,756))

Units: RLC/Year

change in perceived pc food maize supply=
(availability per capita per day kcal group 1-perceived food supply maize)/time to perceive food group
1 supply

Units: kcal/(Year*person*day)

change in perceived per hectare group 1 profit=
(group 1 profit per hectare-perceived group 1 profit per hectare)/time to perceive per hectare group 1
profit

Units: RLC/(Year*Year*ha)

change of aggregated farm income=
(total farm income-aggregated farm income real)/time to adjust farm income

Units: RLC/Year/Year

effect of food supply group 1 on share sold intercept=
0.055

Units: Dmnl

effect of food supply group 1 on share sold slope=
0.48

Units: Dmnl

effect of land rent on share sold intercept=
0.0862

Units: Dmnl

effect of land rent on share sold slope=

0.328164

Units: Dmnl

farm expenditure for fertilizer and soil improvement=

$\max(\text{share of income to fertilizer and soil improvement}, 0) * \text{aggregated farm income real}$

Units: RLC/Year

This variable represents annual fertilizer expenditures done by farmers (in real local currency).

farm income group 1 real=

$\text{producer price group 1 fixo} * \text{sales group 1} * \text{KG PER TON}$

Units: RLC/Year

farm income group 2 real=

$\text{producer price group 2} * \text{sales group 2} * \text{KG PER TON}$

Units: RLC/Year

farm income group 3 real=

$\text{sales group 3} * \text{producer price group 3} * \text{KG PER TON}$

Units: RLC/Year

fertilizer expenditure real=

$\text{farm expenditure for fertilizer and soil improvement} * \text{share of agricultural expenditure to fertilizer}$

Units: RLC/Year

fertilizer subsidies=

200

Units: RLC/Year

190

group 1 producer price intercept=

0.2539

Units: RLC/kg

group 1 producer price slope=

-0.027

Units: Dmnl

group 1 production per farm=

$\text{AREA HARVESTED group 1 per farm} * \text{group 1 yield}$

Units: ton/Year

group 1 profit per hectare=

$\text{per hectare group 1 income} - \text{per hectare fertilizer expenditure} - \text{per hectare expenditure for soil improvement}$

Units: RLC/(Year*ha)

group 1 yield=

$\text{Yield plateau} * \text{effect of nitrogen on yield} * \text{effect of water on yield}$

Units: ton/(ha*Year)

This variable represents average maize yields and is the result the Mitscherlich-Baule production function (Schilling 2000, p.230). Note that the yields are determined using an operational approach: instead of factor application I use factor uptake.

indicated share of production sold from group 1 availability=

$\text{effect of food supply group 1 on share sold intercept} + \text{effect of food supply group 1 on share sold slope} * \text{relative perceived food group 1 supply}$

Units: Dmnl

indicated share of production sold from group 1 profitability=relative perceived group 1 profit per hectare*effect of land rent on share sold slope
+effect of land rent on share sold intercept
Units: Dmnl

initial perceived food supply group 1=
650
Units: kcal/(person*day)

initial perceived group 1 profit per hectare=
150
Units: RLC/(Year*ha)
F1 = 400

KG PER TON=
1000
Units: kg/ton
This variable represents the number of kilograms per metric ton (1000).

nitrogen fertilizer applied to group 1=
nitrogen fertilizer application*share of nitrogen to group 1
Units: ton/Year
This variable represents the total annual nitrogen fertilizer application to maize.

nitrogen fertilizer price real=
1.82
Units: RLC/kg
AVG 1984-2012 calculated from Data: 615

per hectare expenditure for soil improvment=soil improvement expenditure real/total planted area
Units: RLC/(Year*ha)

per hectare fertilizer expenditure=
(nitrogen fertilizer price real*nitrogen fertilizer applied to group 1*KG PER TON)/AREA
HARVESTED group 1 per farm
Units: RLC/(Year*ha)

per hectare group 1 income=
group 1 yield*producer price group 1 fixo*KG PER TON
Units: RLC/(Year*ha)

perceived food supply maize= INTEG (
change in perceived pc food maize supply,initial perceived food supply group 1)
Units: kcal/(person*day)

perceived group 1 profit per hectare= INTEG (
change in perceived per hectare group 1 profit,initial perceived group 1 profit per hectare)
Units: RLC/(Year*ha)

producer price group 1 fixo=
group 1 producer price intercept* EXP(group 1 producer price slope*relative time for group 1)
Units: RLC/kg

relative perceived food group 1 supply=
perceived food supply maize/initial perceived food supply group 1
Units: Dmnl

relative perceived group 1 profit per hectare=
perceived group 1 profit per hectare/initial perceived group 1 profit per hectare

Units: Dmnl

relative time for group 1=

Time-2014

Units: Dmnl

relative weight of profitability in sales decision=

0.5

Units: Dmnl

sales group 1=

group 1 production per farm*share of group 1 production sold

Units: ton/Year

share of agricultural expenditure to fertilizer=

0.25

Units: Dmnl

share of agricultural expenditure to soil improvement=

1-share of agricultural expenditure to fertilizer

Units: Dmnl

share of fertilizer expenditure on nitrogen=

0.7

Units: Dmnl

0.75 This constant represents the share of total fertilizer expenditures going to nitrogen. It was estimated on data for Zambia.

share of group 1 production sold=

Min(indicated share of production sold from group 1 profitability*relative weight of profitability in sales decision

+indicated share of production sold from group 1 availability*(1-relative weight of profitability in sales decision)1)

Units: Dmnl

share of income to fertilizer and soil improvement=

0.3

Units: Dmnl

AVG 1984-2009 calculated from Estimates: 0.57 0.425373

soil improvement expenditure real=

farm expenditure for fertilizer and soil improvement*share of agricultural expenditure to soil improvement

Units: RLC/Year

time to adjust farm income=

1

Units: Year

time to perceive food group 1 supply=

0.4

Units: Year

time to perceive per hectare group 1 profit=

1

Units: Year

total farm income=

farm income group 1 real+"average household off-farm income"+farm income group 2 real
+farm income group 3 real+"average household non-agriculture income"

Units: RLC/Year

total fertilizer expenditures real=
fertilizer expenditure real+fertilizer subsidies

Units: RLC/Year

This variable represents the total annual fertilizer expenditure including private and public sources (in real local currency).

total nitrogen fertilizer expenditure real=
total fertilizer expenditures real*share of fertilizer expenditure on nitrogen

Units: RLC/Year

This variable represents the annual amount of total fertilizer expenditures going to nitrogen (in real local currency).

A.2.10. Sector: Farm Decisions – Group 2

AREA HARVESTED group 2 per farm=
total planted area*Share Group 2

Units: ha

availability of food in kcal per capita per day=
per capita food availability kcal per year/days per year

Units: kcal/(person*day)

availability per capita per day kcal group 2=
per capita kcal group 2/days per year

Units: kcal/(person*day)

change in perceived pc food maize supply 0=
(availability per capita per day kcal group 2-perceived food supply group 2)/time to perceive food group 2 supply

Units: kcal/(Year*person*day)

change in perceived per hectare group 2 profit=
(group 2 profit per hectare-perceived group 2 profit per hectare)/time to perceive per hectare group 2 profit

Units: RLC/(Year*Year*ha)

effect of food supply group 2 on share sold intercept=
0.13

Units: Dmnl

effect of food supply group 2 on share sold slope=
-0.08

Units: Dmnl

effect of land rent on share sold intercept 0=
0.0862

Units: Dmnl

effect of land rent on share sold slope 0=
0.328164

Units: Dmnl

farm income group 2 real=
producer price group 2*sales group 2*KG PER TON

Units: RLC/Year

group 2 production per farm=

AREA HARVESTED group 2 per farm*group 2 yield
Units: ton/Year

group 2 profit per hectare=
per hectare group 2 income-per hectare fertilizer expenditure group 2 field
-per hectare expenditure for soil improvement 0
Units: RLC/(Year*ha)

group 2 yield=
Yield plateau group 2*effect of nitrogen on group 2 yield*effect of water on group 2 yield
Units: ton/(ha*Year)

indicated share of production sold from group 1 profitability 0=
relative perceived group 2 profit per hectare*effect of land rent on share sold slope 0+effect of land rent
on share sold intercept 0
Units: Dmnl

indicated share of production sold from group 2 availability=
effect of food supply group 2 on share sold intercept+effect of food supply group 2 on share sold slope
*relative perceived food group 2 supply
Units: Dmnl

initial perceived food supply group 2=
160
Units: kcal/(person*day)

initial perceived group 2 profit per hectare=
760
Units: RLC/(Year*ha)

KG PER TON=
1000
Units: kg/ton

nitrogen fertilizer applied to group 2=
nitrogen fertilizer application 0*share of nitrogen to group 2
Units: ton/Year

nitrogen fertilizer price real=
1.82
Units: RLC/kg

per hectare expenditure for soil improvement 0=
soil improvement expenditure real/total planted area
Units: RLC/(Year*ha)

per hectare fertilizer expenditure group 2 field=
(KG PER TON*nitrogen fertilizer applied to group 2*nitrogen fertilizer price real)/AREA
HARVESTED group 2 per farm
Units: RLC/(Year*ha)

per hectare group 2 income=
group 2 yield*producer price group 2*KG PER TON
Units: RLC/(Year*ha)

perceived food supply group 2= INTEG (
change in perceived pc food maize supply 0,
initial perceived food supply group 2)
Units: kcal/(person*day)

perceived group 2 profit per hectare= INTEG (
change in perceived per hectare group 2 profit,initial perceived group 2 profit per hectare)
Units: RLC/(Year*ha)

producer price group 2=
producer price group 2 intercept * EXP(producer price group 2 slope*relative time for group 2 price)
Units: RLC/kg

producer price group 2 intercept=
0.5673
Units: RLC/kg

producer price group 2 slope=
-0.005
Units: Dmnl

relative perceived food group 2 supply=
perceived food supply group 2/initial perceived food supply group 2
Units: Dmnl

relative perceived group 2 profit per hectare=
perceived group 2 profit per hectare/initial perceived group 2 profit per hectare
Units: Dmnl

relative time for group 2 price=
Time-2014
Units: Dmnl

relative weight of profitability in sales decision 0=
0.3
Units: Dmnl

sales group 2=
group 2 production per farm*share of group 2 production sold
Units: ton/Year

share of group 2 production sold=
Min(indicated share of production sold from group 1 profitability 0*relative weight of profitability in
sales decision 0+indicated share of production sold from group 2 availability*(1-relative weight of profitability
in sales decision 0),1)
Units: Dmnl

SIZE OF THE HOUSEHOLD= INTEG (
(household births-household deaths),
initial Size of The Household)
Units: person

time to perceive food group 2 supply=
0.3
Units: Year

time to perceive per hectare group 2 profit=
0.8
Units: Year

A.2.11. Sector: Farm Decisions – Group 3

AREA HARVESTED group 3 per farm=
total planted area*Share Group 3

Units: ha

farm income group 3 real=
sales group 3*producer price group 3*KG PER TON
Units: RLC/Year

group 3 production=
AREA HARVESTED group 3 per farm*group 3 yield
Units: ton/Year

group 3 yield=
Yield plateau group 3*effect of nitrogen on yield 1*effect of water on yield 1
Units: ton/(ha*Year)

INITIAL TIME = 2015
Units: Year

KG PER TON=
1000
Units: kg/ton

producer price group 3=
producer price group 3 intercept * EXP(producer price group 3 slope*relative time)
Units: RLC/kg

producer price group 3 intercept=
0.2843
Units: Dmnl

producer price group 3 slope=
0.0144
Units: Dmnl

relative time=
Time-1995
Units: Dmnl

sales group 3=
group 3 production*share of group 3 production sold
Units: ton/Year

Share Group 3=
SMOOTH N(((indicated share of group 3 from perceived risk*0.4)+(indicated share of group 3 from perceived soil fertility*0.1)+(indicated share of group 3 from total planted area*0.1)+(indicated share of group 3 from market price*0.3)+(indicated share of group 3 from distance to market*0.1))*(indicated share of group 3 from share of group 1),3,(((indicated share of group 3 from perceived risk*0.4)+(indicated share of group 3 from perceived soil fertility*0.1)+(indicated share of group 3 from total planted area*0.1)+(indicated share of group 3 from market price*0.3)+(indicated share of group 3 from distance to market*0.1))*(indicated share of group 3 from share of group 1),1)
Units: Dmnl

share of group 1 production sold=
Min(indicated share of production sold from group 1 profitability*relative weight of profitability in sales decision+indicated share of production sold from group 1 availability*(1-relative weight of profitability in sales decision),1)
Units: Dmnl

share of group 3 production sold=
1
Units: Dmnl

total planted area= INTEG (
 increase of field-ABANDON FIELDS,initial planted area)
Units: ha

A.2.12. Sector: Food Availability

aggregated farm income real= INTEG (
 change of aggregated farm income,1000)
Units: RLC/Year

availability of food in kcal per capita per day=
 per capita food availability kcal per year/days per year
Units: kcal/(person*day)

availability per capita per day kcal group 1=
 per capita kcal group 1/days per year
Units: kcal/(person*day)

availability per capita per day kcal group 2=
 per capita kcal group 2/days per year
Units: kcal/(person*day)

Average Dietary Energy Requirement=
 2200
Units: kcal/(person*day)

This variable represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organisation of the United Nations (FAO) that calculate this parameter dependent on several population characteristics (e.g. age structure, level of physical activity, etc.). While the FAO value slightly changes over time, for simplicity, I assume a constant value of 2200 being realistic for the Sub-Saharan Africa region.

average price of monthly food basket= WITH LOOKUP (
 Time,
 ([(2015,200)-(2025,300)],(2015,209.9),(2016,232.8),(2017,246.7),(2018,253.5
),(2019,257.1),(2020,259.2),(2021,260.4),(2022,261.1),(2023,261.6),(2024,261.9
),(2025,262.1)))
Units: RLC

This variable represents the average price of one food basket. The trend was calculated based on the JRCT prices

days per year=
 365

Units: day/Year

This variable represents the number of days per year (365).

energy share of group 1 on total diet=
 0.5

Units: Dmnl

This variable represents the intended share of kilocalories coming from maize compared to the total diet. In Sub-Saharan African countries where maize is the staple crop this share is typically high (40%-70%).

energy share of group 2 on total diet=
 0.25

Units: Dmnl

food energy requirement=

(Average Dietary Energy Requirement*energy share of group 1 on total diet)+(Average Dietary Energy Requirement*energy share of group 2 on total diet)

Units: kcal/(person*day)

group 1 for non food use=
group 1 for seed use+(Share of group 1 production to animal fodder+share of group 1 production waste)

Units: ton/Year

This variable represents the annual maize demand for non-food purposes including seed, animal fodder and food waste.

group 1 production per farm=
AREA HARVESTED group 1 per farm*group 1 yield

Units: ton/Year

group 2 for non food use=
group 1 for seed use 0+(Share of group 2 production to animal fodder+share of group 2 production waste)

Units: ton/Year

group 2 production per farm=
AREA HARVESTED group 2 per farm*group 2 yield

Units: ton/Year

kcal in one food basket=
400000

Units: kcal

kcal per kg group 1=
3071

Units: kcal/kg

This variable represents the number of kilocalories per kilogram maize. It is estimated from FAO data.

kcal per kg group 2=
2400

Units: kcal/kg

2100 weighted average of the group 2 crops

KG PER TON=
1000

Units: kg/ton

This variable represents the number of kilograms per metric ton (1000).

number of food baskets bought per year=
total farm income for buying food/average price of monthly food basket

Units: Dmnl/Year

per capita food availability kcal per year=
total food availability in kcal/SIZE OF THE HOUSEHOLD

Units: kcal/(Year*person)

per capita food basket kcal=
total kcal availability from food baskets/SIZE OF THE HOUSEHOLD

Units: kcal/(Year*person)

per capita kcal group 1=
total food availability group 1 in kcal/SIZE OF THE HOUSEHOLD

Units: kcal/(Year*person)

per capita kcal group 2=
total food availability group 2 in kcal/SIZE OF THE HOUSEHOLD

Units: kcal/(Year*person)

per capita per day kcal food basket=
per capita food basket kcal/days per year

Units: kcal/(person*day)

sales group 1=

group 1 production per farm*share of group 1 production sold

Units: ton/Year

sales group 2=

group 2 production per farm*share of group 2 production sold

Units: ton/Year

share group 1 on diet=

0.5

Units: Dmnl

share group 2 on diet=

0.25

Units: Dmnl

share of farm income to food=

0.6

Units: Dmnl

SIZE OF THE HOUSEHOLD= INTEG (

(household births-household deaths),initial Size of The Household)

Units: person

total farm income for buying food=

aggregated farm income real*share of farm income to food

Units: RLC/Year

total food availability group 1 in kcal=

kcal per kg group 1*KG PER TON*total food group 1 availability in tons

Units: kcal/Year

total food availability group 2 in kcal=

kcal per kg group 2*KG PER TON*total food group 2 availability in tons

Units: kcal/Year

total food availability in kcal=

(total food group 1 availability in tons*KG PER TON*kcal per kg group 1)+(total food group 2 availability in tons*KG PER TON*kcal per kg group 2)+total kcal availability from food baskets

Units: kcal/Year

total food group 1 availability in tons=

((group 1 production per farm)-(sales group 1+group 1 for non food use))*share group 1 on diet

Units: ton/Year

This variable represents the total number of tons from maize products that are available for human consumption per year.

total food group 2 availability in tons=

((group 2 production per farm)-(sales group 2+group 2 for non food use))*share group 2 on diet

Units: ton/Year

total kcal availability from food baskets=

kcal in one food basket*number of food baskets bought per year

Units: kcal/Year

A.2.13. Sector: Crop Decisions

ABANDON FIELDS=

$$\text{DELAY N}(\text{total planted area} * 0.08 / \text{time to abandon field}, 2, \text{total planted area} * 0.08 / \text{time to abandon field}, 3)$$
 Units: ha/Year

age of HHh=

$$\text{initial HHh age} + (\text{Time} - 2015)$$
 Units: Year

aggregated farm income real= INTEG (

$$\text{change of aggregated farm income}, 1000)$$
 Units: RLC/Year

availability of food in kcal per capita per day=

$$\text{per capita food availability kcal per year} / \text{days per year}$$
 Units: kcal/(person*day)

availability per capita per day kcal group 1=

$$\text{per capita kcal group 1} / \text{days per year}$$
 Units: kcal/(person*day)

average distance to market=
 10
 Units: km

average planted area per household member=
 0.3
 Units: ha
 calculated from data

change in perceived farm income=

$$\text{DELAY N}((\text{aggregated farm income real} - \text{perceived farm income}) / \text{time to perceive farm income}, 1, (\text{aggregated farm income real} - \text{perceived farm income}) / \text{time to perceive farm income}, 3)$$
 Units: RLC/(Year*Year)

change in perceived pc food supply=

$$\text{DELAY N}((\text{availability of food in kcal per capita per day} - \text{perceived food supply}) / \text{time to perceive food supply}, 1, (\text{availability of food in kcal per capita per day} - \text{perceived food supply}) / \text{time to perceive food supply}, 1)$$
 Units: kcal/(Year*person*day)

change in perceived soil fertility in group 3 field=

$$(\text{relative soil fertility group 3 field} - \text{perceived soil fertility in group 3 field}) / \text{time to perceive change in soil fertility in group 3 field}$$
 Units: Dmnl/Year

change in perceived soil fertility=

$$(\text{relative yield} - \text{perceived soil fertility}) / \text{time to perceive change in soil fertility}$$
 Units: Dmnl/Year

change on perceived risk=

$$(\text{effect of aging on perceived risk to plant cash crops} - \text{perceived risk}) / \text{time to perceive change in risk}$$
 Units: Dmnl/Year

days per year=
 365
 Units: day/Year
 This variable represents the number of days per year (365).

desired availability of food in kcal=
 2056
 Units: kcal/(day*person)

desired food availability in kcal per capita per day=
share group 1 on diet*desired availability of food in kcal
Units: kcal/(day*person)

desired food availability in kcal per capita per day group 2=
share group 2 on diet*desired availability of food in kcal
Units: kcal/(day*person)

desired per household kcal cal group 2 per year=
days per year*desired food availability in kcal per capita per day group 2
*SIZE OF THE HOUSEHOLD
Units: kcal/Year

desired per household kcal group 1 per year=
desired food availability in kcal per capita per day*SIZE OF THE HOUSEHOLD
*days per year
Units: kcal/Year

distance to market=
(districtal distance to market slope*district)
Units: km

district=
3
Units: Dmnl

districtal distance to market slope=
4
Units: km

effect of aging on perceived risk to plant cash crops=
relative age^elasticity of age to perceiving risk
Units: Dmnl

effect of availability of food on increasing field slope=
0.45
Units: ha

effect of disposable income on propensity to increase field slope=
-0.15
Units: ha

effect of distance to market on share of group 3 slope=
-0.082
Units: Dmnl

effect of gender on propensity to plant group 2 crops slope=
0.84
Units: Dmnl

effect of hired labor on share group 1 slope=
0.5
Units: Dmnl

effect of household size slope=
0.35
Units: ha

effect of perceived risk on share of group 3 slope=

-0.3
Units: Dmnl

effect of perceived soil fertility on increased field=
-0.1
Units: ha

effect of share of group 3 on share of group 2=
-2
Units: Dmnl

effect of share of group 3 on share of group 3=
-1.8
Units: Dmnl

effect of soil fertility on share of group 3 slope=
-0.6
Units: Dmnl
estimated from data

effect of total planted area on share of group 1 slope=
0.3
Units: Dmnl
estimated from data (index vs. tt_planted_area)

effect of total planted area on share of group 3 slope=
-0.09
Units: Dmnl
estimated from data

effect of total plantes area on share of group 2 slope=
-0.06
Units: Dmnl

elasticity=
0.3
Units: Dmnl

elasticity 1=
0.14
Units: Dmnl

elasticity of age to perceiving risk=
1.2
Units: Dmnl

elasticity of income to share of group 2=
0.9
Units: Dmnl

elasticity of market price to share of group 3=
0.8
Units: Dmnl

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farm expenditure for hirng labor=
share of income to hiring labor*aggregated farm income real
Units: RLC/Year

gender HHH=

0
Units: Dmnl

group 1 yield=
Yield plateau*effect of nitrogen on yield*effect of water on yield
Units: ton/(ha*Year)

group 2 yield=
Yield plateau group 2*effect of nitrogen on group 2 yield*effect of water on group 2 yield
Units: ton/(ha*Year)

group 3 yield=
Yield plateau group 3*effect of nitrogen on yield 1*effect of water on yield 1
Units: ton/(ha*Year)

groups yield=
group 1 yield+group 2 yield+group 3 yield
Units: ton/(Year*ha)

household births=
SIZE OF THE HOUSEHOLD*household growing rate
Units: person/Year

household death rate=
0.009
Units: Dmnl/Year
<https://knoema.com/atlas/Zambia/Population-growth>

household deaths=
SIZE OF THE HOUSEHOLD*household death rate
Units: person/Year

household growing rate=
0.04
Units: Dmnl/Year
<https://knoema.com/atlas/Zambia/Population-growth>

household total labor=
DELAY N(share of household members engaged on farm labor*SIZE OF THE HOUSEHOLD ,5,share of household members engaged on farm labor*SIZE OF THE HOUSEHOLD,3)
Units: person

increase of field=
DELAY N(((indicated increased field from food supply*0.4)+(indicated increased field from perceived income*0.1)+(indicated planted area from household size*0.3)+(indicated increased field from perceived soil fertility*0.2)),time to use increase field,(indicated increased field from food supply*0.4)+(indicated increased field from perceived income*0.1)+(indicated planted area from household size*0.3)+(indicated increased field from perceived soil fertility *0.2),1)
Units: ha/Year

indicated increased field from food supply=
relative perceived food supply*effect of availability of food on increasing field slope
Units: ha

indicated increased field from perceived soil fertility=
relative perceived soil fertility*effect of perceived soil fertility on increased field
Units: Dmnl

indicated increased field from perceived income=

(relative perceived farm income*effect of disposable income on propensity to increase field slope)
Units: ha

indicated planted area from household size=
DELAY N((effect of household size slope*relative size of the household),5,effect of household size slope*relative size of the household,3)
Units: ha

indicated share of group 1 from food supply group 1=
intercept+(relative desired increase*slope 0)
Units: Dmnl

indicated share of group 1 from labor availability=
DELAY N (effect of hired labor on share group 1 slope*relative available labor,1,effect of hired labor on share group 1 slope*relative available labor,1)
Units: Dmnl

indicated share of group 1 from profit=
relative perceived group 1 profit per hectare^elasticity
Units: Dmnl

indicated share of group 1 from total planted area=
relative total planted area*effect of total planted area on share of group 1 slope
Units: Dmnl

indicated share of group 2 from farm income=
(relative perceived farm income^elasticity of income to share of group 2)/10
Units: Dmnl

indicated share of group 2 from food supply group 2=
intercept1+(slope 1*relative desired increase group 2)
Units: Dmnl

indicated share of group 2 from gender=
(effect of gender on propensity to plant group 2 crops slope*gender HHH)
Units: Dmnl

indicated share of group 2 from profit=
relative perceived group 2 profit per hectare*elasticity 1
Units: Dmnl

indicated share of group 2 from share of group 1=
relative share of group 1^effect of share of group 3 on share of group 2
Units: Dmnl

indicated share of group 2 from total planted area=
(relative total planted area*effect of total planted area on share of group 2 slope)
Units: Dmnl

indicated share of group 3 from distance to market=
(effect of distance to market on share of group 3 slope*relative distance to market)
Units: Dmnl

indicated share of group 3 from market price=
relative producer price group 3^elasticity of market price to share of group 3
Units: Dmnl

indicated share of group 3 from perceived risk=
DELAY N(relative perceived risk*effect of perceived risk on share of group 3 slope ,3,relative perceived risk*effect of perceived risk on share of group 3 slope,3)

Units: Dmnl

indicated share of group 3 from perceived soil fertility=
relative perceived soil fertility in group 3 field*effect of soil fertility on share of group 3 slope

Units: Dmnl

indicated share of group 3 from share of group 1=
relative share of group 1^effect of share of group 3 on share of group 3

Units: Dmnl

indicated share of group 3 from total planted area=
(relative total planted area*effect of total planted area on share of group 3 slope)

Units: Dmnl

initial average yield= INITIAL(
groups yield)

Units: ton/(Year*ha)

initial desired increase= INITIAL(
total desired increase)

Units: ton/Year

initial desired increase group 2= INITIAL(
total desired increase group 2)

Units: ton/Year

initial group 3 yield= INITIAL(
group 3 yield)

Units: ton/(Year*ha)

initial HHh age=
35

Units: Year

initial hired labor= INITIAL(
total hired labor)

Units: day/Year

initial household total labor= INITIAL(
household total labor)

Units: person

initial perceived farm income= INITIAL(
950)

Units: RLC/Year

initial perceived food supply= INITIAL(
1100)

Units: kcal/(person*day)

initial perceived risk=
1

Units: Dmnl

initial perceived soil fertility group 3=
1

Units: Dmnl

initial planted area=
initial Size of The Household*average planted area per household member

Units: ha

initial producer price gorup 3= INITIAL(
producer price group 3)

Units: RLC/kg

initial relative desired increase=
1.2

Units: Dmnl

initial share of group 1= INITIAL(
Share Group 1)

Units: Dmnl

initial Size of The Household=
5

Units: person

initial perceived soil fertility=
1.22

Units: Dmnl

intercept=
0.063

Units: Dmnl

intercept1=
0.25

Units: Dmnl

kcal per kg group 1=
3071

Units: kcal/kg

This variable represents the number of kilocalories per kilogram maize. It is estimated from FAO data.

kcal per kg group 2=
2400

Units: kcal/kg

2100 weighted average of the group 2 crops

KG PER TON=
1000

Units: kg/ton

This variable represents the number of kilograms per metric ton (1000).

mean wage hired labor per day=
3

Units: RLC/day

perceived farm income= INTEG (
change in perceived farm income, initial perceived farm income)

Units: RLC/Year

perceived food supply= INTEG (
change in perceived pc food supply, initial perceived food supply)

Units: kcal/(person*day)

perceived risk= INTEG (
change on perceived risk, initial perceived risk)

Units: Dmnl

perceived soil fertility in group 3 field= INTEG (change in perceived soil fertility in group 3 field,initial perceived soil fertility group 3)
Units: Dmnl

perceived soil fertility= INTEG (change in perceived soil fertility,initial perceived soil fertility)
Units: Dmnl

producer price group 2=
producer price group 2 intercept * EXP(producer price group 2 slope*relative time for group 2 price)
Units: RLC/kg

producer price group 3=
producer price group 3 intercept * EXP(producer price group 3 slope*relative time)
Units: RLC/kg
 $y = 0.0043x + 0.3046$

relative age=
age of HHh/initial HHh age
Units: Dmnl

relative available labor=
relative household total labor*relative hired labor
Units: Dmnl

relative desired increase= DELAY FIXED (total desired increase/initial desired increase,0,initial relative desired increase)
Units: ton/Year

relative desired increase group 2= DELAY FIXED (total desired increase group 2/initial desired increase group 2,0,1)
Units: Dmnl

relative distance to market=
distance to market/average distance to market
Units: km

relative hired labor=
total hired labor/initial hired labor
Units: Dmnl

relative household total labor=
household total labor/initial household total labor
Units: Dmnl

relative perceived farm income=
perceived farm income/initial perceived farm income
Units: Dmnl

relative perceived food group 2 supply=
perceived food supply group 2/initial perceived food supply group 2
Units: Dmnl

relative perceived food supply=
perceived food supply/initial perceived food supply
Units: Dmnl

relative perceived group 1 profit per hectare=
perceived group 1 profit per hectare/initial perceived group 1 profit per hectare

Units: Dmnl

relative perceived group 2 profit per hectare=
perceived group 2 profit per hectare/initial perceived group 2 profit per hectare

Units: Dmnl

relative perceived risk=
perceived risk/initial perceived risk

Units: Dmnl

relative perceived soil fertility=
perceived soil fertility/initial perceived soil fertility

Units: Dmnl

relative perceived soil fertility in group 3 field=
perceived soil fertility in group 3 field/initial perceived soil fertility group 3

Units: Dmnl

relative producer price group 3=
producer price group 3/initial producer price group 3

Units: Dmnl

relative share of group 1=
Share Group 1/initial share of group 1

Units: Dmnl

relative size of the household=
SIZE OF THE HOUSEHOLD/initial Size of The Household

Units: Dmnl

relative soil fertility group 3 field=
group 3 yield/initial group 3 yield

Units: Dmnl/Year

relative total planted area=
total planted area/initial planted area

Units: Dmnl

relative yield=
groups yield/initial average yield

Units: Dmnl

Share Group 1=

SMOOTH N((indicated share of group 1 from food supply group 1*0.6)+(indicated share of group 1 from labor availability*0.1)+(indicated share of group 1 from profit*0.2)+(indicated share of group 1 from total planted area*0.1),6,(indicated share of group 1 from food supply group 1*0.6)+(indicated share of group 1 from labor availability*0.1)+(indicated share of group 1 from profit*0.3)+(indicated share of group 1 from total planted area*0.1),3)

Units: Dmnl

share group 1 on diet=
0.5

Units: Dmnl

Share Group 2=

((indicated share of group 2 from gender*0.075)+(indicated share of group 2 from farm income*0.2)+(indicated share of group 2 from total planted area*0.025)+(indicated share of group 2 from food supply group 2*0.4)+(indicated share of group 2 from profit*0.3))*indicated share of group 2 from share of group 1

Units: Dmnl

share group 2 on diet=
0.25

Units: Dmnl

Share Group 3=

SMOOTH N(((indicated share of group 3 from perceived risk*0.4)+(indicated share of group 3 from perceived soil fertility*0.1)+(indicated share of group 3 from total planted area*0.1)+(indicated share of group 3 from market price*0.3)+(indicated share of group 3 from distance to market *0.1))*(indicated share of group 3 from share of group 1),3,((indicated share of group 3 from perceived risk*0.4)+(indicated share of group 3 from perceived soil fertility*0.1)+(indicated share of group 3 from total planted area*0.1)+(indicated share of group 3 from market price*0.3)+(indicated share of group 3 from distance to market*0.1))*(indicated share of group 3 from share of group 1),1)

Units: Dmnl

share of household members engaged on farm labor=
0.5

Units: Dmnl

share of income to hiring labor=
0.1

Units: Dmnl

SIZE OF THE HOUSEHOLD= INTEG (
(household births-household deaths),initial Size of The Household)

Units: person

slope 0=
0.33

Units: Dmnl

slope 1=
0.3

Units: Dmnl

time to abandon field=
1

Units: Year

time to perceive change in risk=
1

Units: Year

time to perceive change in soil fertility=
1

Units: Year

time to perceive change in soil fertility in group 3 field=
1

Units: Year

time to perceive farm income=
1

Units: Year

time to perceive food supply=
1

Units: day

time to use increase field=

2

Units: Year

total desired food availability group 1 in kg per year in ton=
desired per household kcal group 1 per year/kcal per kg group 1/KG PER TON

Units: ton/Year

total desired food availability group 2 in kg per year in ton=
desired per household kcal cal group 2 per year/KG PER TON/kcal per kg group 2

Units: ton/Year

total desired increase=
total desired food availability group 1 in kg per year in ton-total food group 1 availabilty in tons

Units: ton/Year

total desired increase group 2=
total desired food availability group 2 in kg per year in ton-total food group 2 availability in tons

Units: ton/Year

total food availability group 2 in kcal=
kcal per kg group 2*KG PER TON*total food group 2 availability in tons

Units: kcal/Year

total food availability in kcal=
(total food group 1 availability in tons*KG PER TON*kcal per kg group 1)+(total food group 2
availability in tons
*KG PER TON

*kcal per kg group 2)+total kcal availability from food baskets

Units: kcal/Year

This variable represents the total number of kilocalories from maize products that are available for human consumption per year.

total food group 1 availability in tons=
((group 1 production per farm)-(sales group 1+group 1 for non food use))*share group 1 on diet

Units: ton/Year

This variable represents the total number of tons from maize products that are available for human consumption per year.

total food group 2 availability in tons=
((group 2 production per farm)-(sales group 2+group 2 for non food use))*share group 2 on diet

Units: ton/Year

total hired labor=
farm expenditure for hirng labor/mean wage hired labor per day

Units: day/Year

total planted area= INTEG (
increasement of field-ABANDON FIELDS,initial planted area)

Units: ha