A case study on

The Vicious Cycle of Food Insecurity in Small-scale Farmer Households in Zambia

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Farhana

Abbreviations

CSO: Central Statistical Office

FAO: Food and Agriculture Organization (of the United Nations)

FEWS NET: Famine Early Warning Systems Network

FISP: Farmer Input Support Programme

FRA: Food Reserve Agency

GDP: Gross Domestic Product

GHI: Global hunger index

Ha: Hectares

IAPRI: Indaba Agricultural Policy Research Institute

Kg: Kilogram

MAL: Ministry of Agriculture and Livestock

MT: Metric Tons

PoU: Prevalence of Undernourishment

RALS: Rural Agriculture Livelihood Survey

SD: System dynamics

SSA: Sub-Saharan Africa

CLD: Causal loop diagram

SFD: Stock and flow diagrams

SOM: soil organic matter

UN: United Nations.

USD: United States Dollars

WHO: world health organization

WB : World bank

ZMK: Zambian Kwacha

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Abstract

Approximately 11% of the world population is suffering from food insecurity; most of them live in sub-Saharan African countries like Zambia. Almost half of the Zambian people are extremely poor and rely on agriculture for food and livelihood. Due to natural calamities and lack of agricultural facilities, small-scale household farmers can not produce sufficient food, which leads to food scarcity in the lean season. Maize is the main food staple and grown by more than 90% of the small household farmers. Therefore, this study utilized a system dynamic approach and created a simulatory model focusing on the main agricultural product- Maize into the Zambian scenario to assess food insecurity at the household level. The simulated model encompassed various aspects of food insecurity, including food availability, food production, food storage, soil fertility. Food insecurity is assessed from dietary energy consumption to calculate food deficit and prevalence of undernourishment (PoU) at the household level. The behavior analysis of the food security model uncovers the dependency on Maize and its poor yield leading to food insecurity and poverty, further restricting their ability to purchase food and fertilizer, causing deterioration of maize yield in the next season, thus forming a vicious cycle. The study points to several factors responsible for food insecurity, extreme poverty, lack of irrigation, insufficient fertilizer use, and dependency on Maize and post-harvest loss. The study also suggests some policies and test their long-term influence after implementation intending to mitigate the food crisis in Zambia. We formulated five policies, increase fertilizer application, zero post-harvest loss to improve the efficiency of the supply chain, increase soil fertility through adopting conservation agriculture by intercropping and leaving crop residuals on the field, and livestock farming to improve the economic situation. The model indicates that when all the proposed policies are implemented, Maize yield increases significantly, implying them as a feasible strategy to improve food security at the small-scale household level. Finally, the study contributes to the understanding of food insecurity among small-scale household farmers in Zambia and provides some guidelines for the policymakers to mitigate the food insecurity problem.

1 Introduction

1.1 Background

Severe undernourishment is a major global challenge, affecting 821 million people in 2018, which is equivalent to 10.8% of the world population [1]. The prevalence of undernourishment is an indicator to assess food security, which is defined as the uninterrupted supply of safe and nutritious food for everyone. Ensuring food security is an agenda of sustainable development goal 2, zero hunger. However, the world population is steadily growing, which calls for more food provision [2]. Intense cropping and the use of advanced agricultural techniques contribute to a consistent increase in food production. Notwithstanding the increase in global food production, the total number of undernourished people is alarming and still rising. The distribution of food insecurity is sporadic and is more prevalent in the impoverished and developing countries in Asia and Sub-Saharan Africa, which is the most food-insecure region in the world (fig. 1) [3] [1].

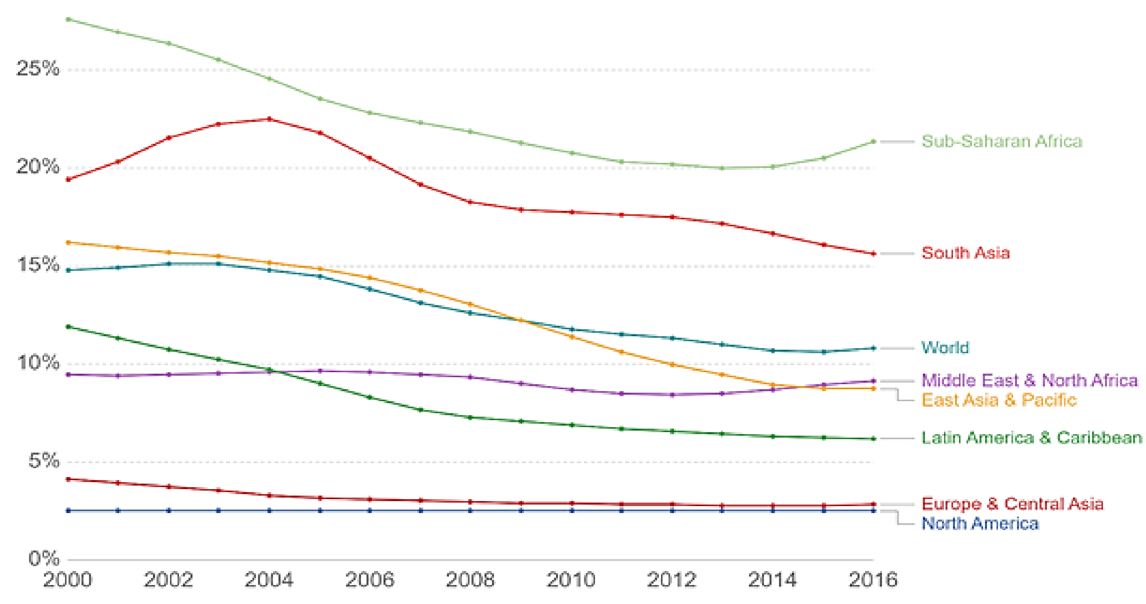


Fig 1: The prevalence of undernourishment – as a percentage of the total population throughout 2000-2017 [4]

Most of the sub-Saharan African countries have a feeble economy, inadequate agriculture production, and poor governance pose a considerable challenge. Here, the prevalence of food insecurity is two times higher than the whole world [5]. The undernourishment in this region showed a declining trend for the last few decades until 2015-2017 when it started to rise again.

Among the region, Zambia has been profoundly affected by a grave food crisis lately. 37 percent of the Zambian population is suffering from food scarcity that makes it among the top five countries in the global hunger index [6]. The majority of the Zambian population lives in agrarian society, and they rely on subsistence agriculture for survival in terms of food and livelihood. To achieve food security, the Zambian government has taken several measures to boost the agricultural sector [7]. However, the goal of zero hunger is beyond the horizon.

1.2 Problem statement

About 6 million Zambian population is prone to food insecurity, making Zambia is one of the most hunger-affected the country in the world [8]. Zambian people have an average dietary energy supply of 2017 kcal/cap/day, which is less than the minimum level of dietary energy consumption [9]. The number of deficient food calories is also referred to as a food deficit; in the case of Zambia, it is 405 Kcal in 2016 [10]. The food deficit in Zambia is increasing sharply since 1997, at an average annual rate of 2.92% (fig. 2).

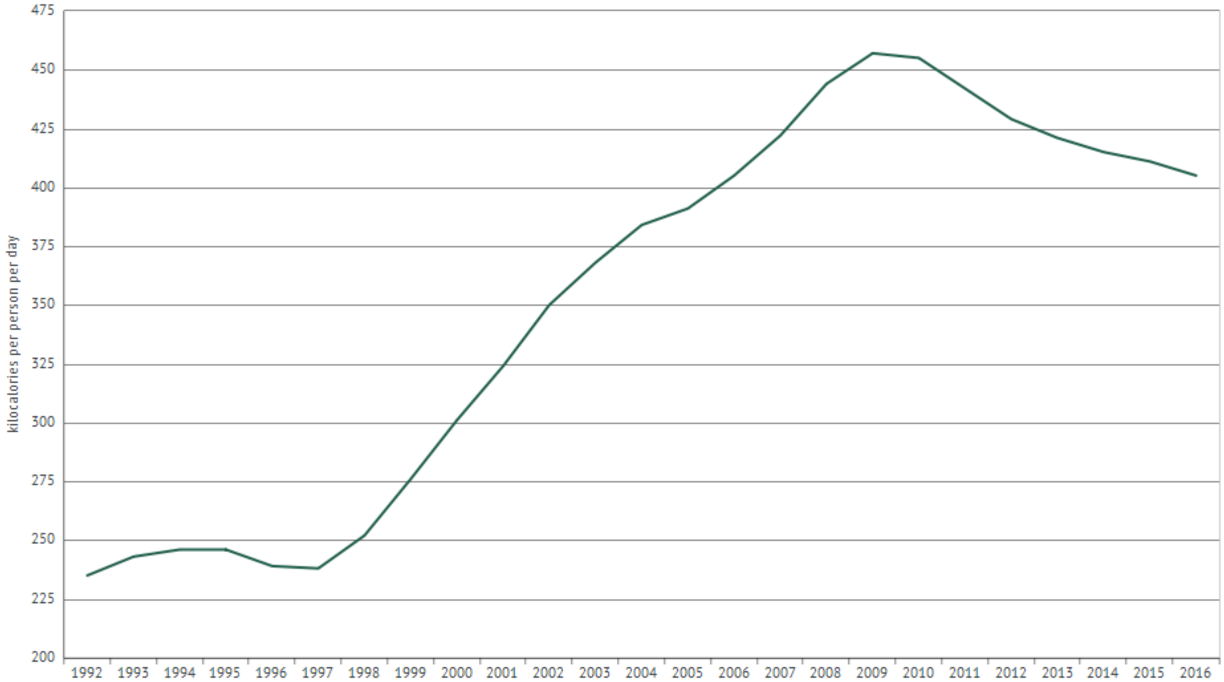


Figure 2: Food deficit (kcal per person per day) in Zambia from 1992 to 2016 [10].

The food insecurity leads to malnutrition and takes a devastating toll on the health of Zambians. The concept of food security is quite elusive, and proper measurement can be difficult. Therefore, several indicators and tools have been proposed to determine food security and facilitate planning, decision-making, and implementation to improve food security. Food Insecurity Experience Scale (FIES) and Prevalence of Undernourishment (PoU) are the most commonly used tools to evaluate food insecurity at the individual level. The prevalence of undernourishment Zambia from 1999-2018 is shown in fig 3. PoU was increasing mildly from 1999 to 2008, whereas it followed a declining trend up to 2016 when it started to rise again. In 2018, the PoU in Zambia was reported at 48.8 % [11].

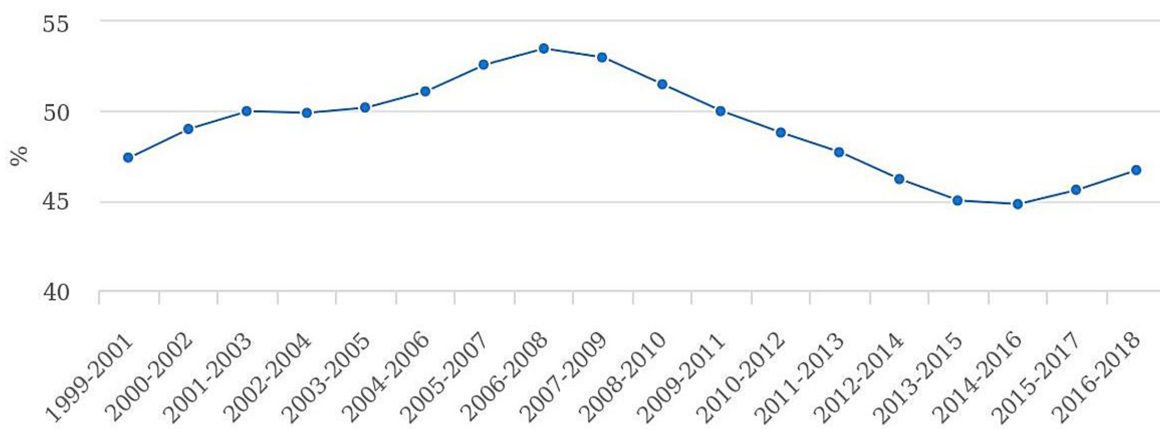


Fig 3: Prevalence of undernourishment (%) at the national level (3-year average) since 1999/2001 [4]

Zambia is one of the poorest countries in the world, with very high-income disparity. 64% of Zambians earn less than the international poverty line, i.e., less than 1.9 US$ per day, which are especially vulnerable to food insecurity [12]. [13]. 45% of Zambian people live in rural areas who have to depend solely on agriculture for survival [3]. Ironically, these small-scale farmers live in extreme poverty even below their country's average. They do not have any alternative source of income, making them immensely vulnerable to hunger for an extended period of the year (Fig 4).

One of Zambian agriculture's main characteristic features is the predominant cropping of the main staple, i.e., Maize. Other factors that are related to describing the condition are unfavorable climate, lack of irrigation system, and other advanced agricultural methods. All of these factors contribute to an unpredictable, ineffective, and often inadequate harvest that is not enough to feed themselves or to afford livelihood for a year. Food availability and price vary widely throughout the harvesting season, creating a food crisis [14].

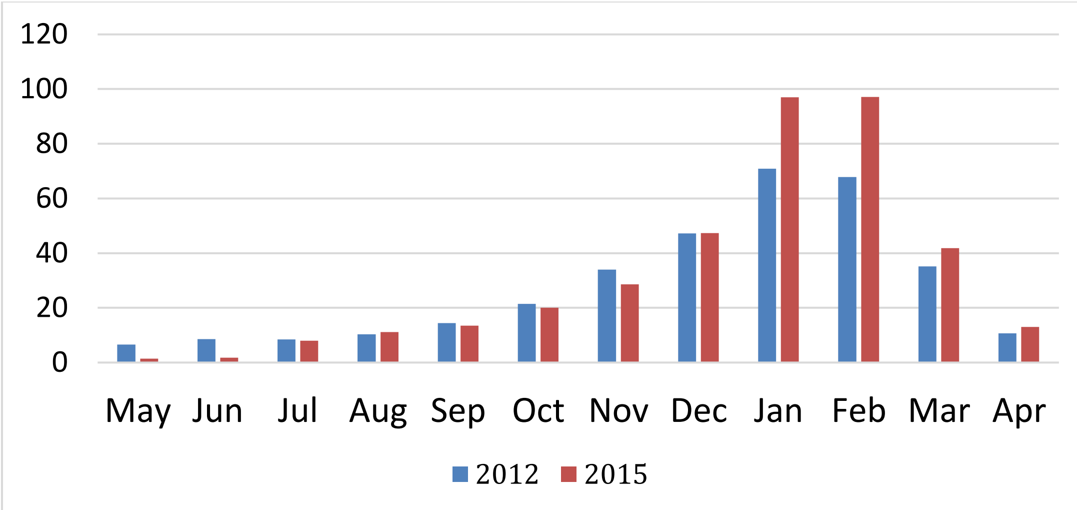


Fig 4: Percentage of households experiencing food insecurity by month in 2012 and 2015 [15]

Fig 4 describes that the monthly prevalence of undernourishment in small-scale farmer households. The percentage of farmers experiencing undernourishment is the most affected during the lean season (November-March). The food reserve becomes maximum in April through August, which also coincides with the minimum food price. The price gradually increases as the food reserve declines giving them food shortages the last few months of the harvesting season i. e. January and February. During this time, approximately 60 percent of farmers experience some degree of food scarcity for up to several months [15]. Due to an imbalance in the supply-demand ratio, the price of the food reaches its peak during this time, making the food more inaccessible for small scale household farmers. The absence of any other income source leaves many householders as food insecure even in years of good harvests because they sell a portion of their harvested crop to meet other necessities.

The causes behind Zambia's poverty and food insecurity are intertwined intricately. The reason behind it can be divided into two groups: natural factors such as unfavorable geography and climate; others are man-made factors such as political conflict, lack of technology, and extreme poverty [16]. Zambia has one of the weakest infrastructures in the region, which is an obstacle towards enough food production, storage, and distribution. As the agriculture in Zambia is dominated by a single harvest of Maize in a year, the management of the produced food is equally important. Besides ineffective levels of food production, there is also an insufficient number of proper storehouses. Inadequate storage capacity and food distribution systems contribute to a poorly managed supply chain and the eventual food insecurity [3].

Government purchases Maize throughout the country at the beginning of the season and store them in the warehouse and used in the latter part of the year. The purchase occurs at low prices, which implies that farmers do not make a good profit by producing and selling food crops [17]. Small-scale farmers have a relatively good supply of food crops that they sell-off in large quantities to meet their other demands of life besides food. They underestimate their need or are forced to sell food in the latter part of the harvest season. This will put them in the vulnerable stage of food insecurity.

Zambia has improved consistently over the decades in terms of economic parameters such as GDP and per capita income leading to development in the areas of rural infrastructure and urbanization.

Nevertheless, economic development did not improve the quality of life for the Zambians. The country has taken six national development plans to reduce poverty and improve living standards to its population, yet the goal to achieve food access to everyone is still far away.

The small-scale householders have poor harvest yield due to their preexisting poverty, which hinders their access to fertilizer and irrigation. Moreover, a significant portion of food is wasted due to a lack of storage capacity and distribution process. Being the sole source of income, the farmers are bound to sell a large proportion of harvested crops to afford other life necessities that expose them to food insecurity in the lean season [18]. Poverty and food insecurity affect each other and initiate a vicious cycle in the Zambian food production scenario that contributes to food insecurity among households. The causes are deep-rooted and interrelated, making it hard to intervene in aiming enough food production to maintain a healthy life.

To ensure the food security in Zambia, a bold, targeted, and coordinated intervention should be taken. Food security is a complex socioeconomic problem where all the factors are connected and affect each other. There is an urgent need for a systematic assessment of the whole system instead of considering the components individually. We have adopted a simulation-based approach that focuses on feedback loops, accumulations and non-linearities among the variables to explain the behavior over time, identify leverage points and formulate some policies to counteract long-standing food insecurity in small- scale farmer households in Zambia.

1.3 Research objectives and questions

1.3.1 Research Objective

The objective of this study is to understand the dynamic complexity of seasonal food insecurity in small-scale farmer households in Zambia. Based on this understanding, the thesis also aims at evaluating the relative effectiveness of different food security policies.

1.3.2 Research question:

The main research question of this study is to identify what are the endogenous reasons behind food production systems that determine the dynamics of seasonal food insecurity in small-scale farming households in Zambia?

The sub-questions of this study are-

1. What are the structure and main feedback loops that explain the seasonal food security phenomenon in small-scale households in Zambia?

2. What are the leverage points that may be deployed to enhance food security sustainably?

3. What are the policy and farm management options that may be utilized to reach adequate and sustainable levels of food availability in small-scale farming households in Zambia?

1.4 Organization of the study:

The thesis is composed of seven chapters. Chapter 1 gives a background of the food insecurity among the small scale household farmers in Zambia. The problem statement illustrates the dependency on Maize and its poor yield leading to food insecurity and poverty, further deteriorating the cause itself, forming a vicious cycle. It is also discussed the rationale of the study, that directs to the research objective and research questions that would be addressed. In chapter 2, an overview of the existing knowledge is given on previous studies food security field. The section also included a detailed explanation of the concept, a systemic review of the food security problem, and the drivers of the system. The chapter also outlines the status of the key agricultural products in Zambia. Chapter 3 explained the rationale of choosing system dynamics as the methodology for the study. Besides, the method data collection and analysis process was described in detail. Chapter 4 described the structure of the model built with stocks, flows, and significant feedback loops to depict how the variables interact with each other. The fifth chapter describes the validation of the created model through several tests to build confidence after comparing the simulation and real-world data. Section six comprises of the discussion of the behavior analysis of the simulation model followed by the analysis of the policies formulated from the model. At the same time, a short explanation of the possible implications of the policies was also given. Finally, chapter seven concludes the thesis by summarizing the critical findings, limitations o and future perspectives of the study.

2 Literature Review

This chapter reviews relevant literature that lays the foundation of the concept and the sources of data for the study. It begins by defining food security, explaining its different dimensions, and an overview of the worldwide food security trends with a particular focus on the Zambian scenario. Relevant data from seasonal crop production, agriculture land, and subsidies in Zambia small scale farmer household level were entered to formulate the model. The literature provided an insight that is fundamental to unlock the solution of household food insecurity in Zambia so that appropriate actions can be taken.

2.1 Definition of concepts

2.1.1 Food insecurity

The issue of food security is extensively studied, and numerous explicit and implied definitions have been underlined [19]. The most widely accepted definition is made by FAO which states it as- “a situation when all people, at all times, have physical social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life" [20]

The initial concept to describe food insecurity focused mainly on the availability and access to the food supply, which is later turned out to be a flexible concept, and expanded over the last few decades. The concept of food insecurity has included various temporal dynamics and evolved from an individual level to the globally stretching multifactorial and complex problem. Gradually, in addition to sufficient, safe and nutritious food, emphasis started to place on the associated factors such as low income, poor governance, and vulnerability to natural disasters, or conflict leading to transitory food insecurity. However, in the 1980s, the entitlement theory by Amartya Sen shifted the focus of food security on to the household and individual perspective [20]. Food insecurity can be inflicted by food unavailability, food price beyond affordability, poor distribution at any level from production to the household level (Fig 5).

The current definition of food security rests on the following four pillars- availability, access, utilization, and stability. The state of food security based on these points can be evaluated at a different level at the national, regional, household, or individual level. Moreover, results may vary based on the method of data collection.

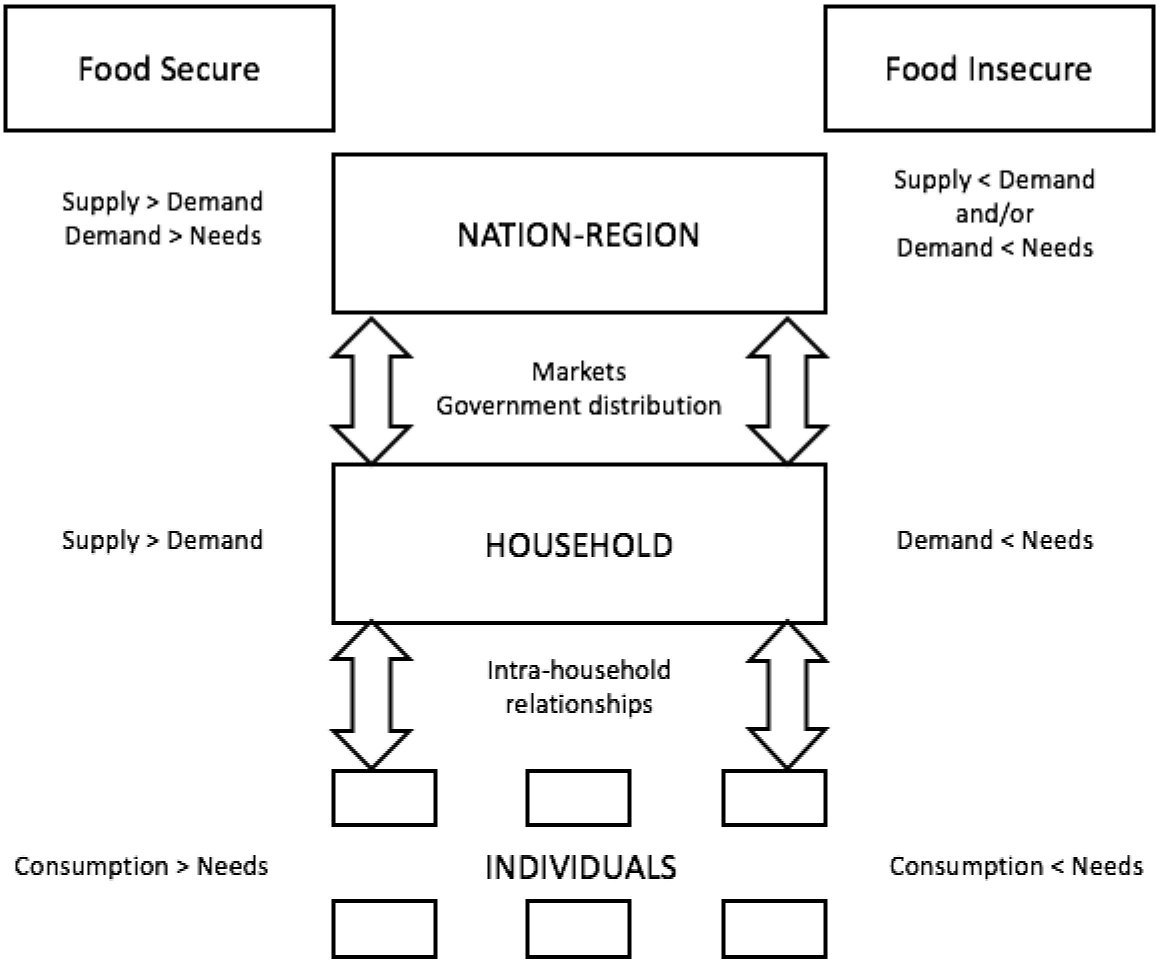


Figure 5: Assessment of food security at different level [21]

2.1.1.1 Food availability:

Food availability is defined as the consistent supply of sufficient and appropriate food to all people, which is possible through domestic food production, food trade, and food aid. The earliest attempt to describe food security described by Malthus in his Food Availability Decline (FAD) theory in 1798 stated that insufficient food supply is the main reason for food insecurity. FAD theory measured the ratio of available daily calories versus the demand per person, which is, in fact, an oversimplification of the problem [22]. The limitation of FAD theory is that it does not address the regional variation of the available food, supplemented by Amartya Sen's entitlement approach in his book poverty and famine. This theory addresses the socioeconomic perspectives of food scarcity, such as conflict, poor trade, lack of aid supply [23]. The concept has evolved to be recognized as a problem not only associated with a problem with food production but also the distribution of it. Studies showed that the world is producing adequate food to feed everyone, but the inefficient distribution of scarce resource leads to food insecurity.

Similarly, food security at the global or national level does not necessarily ensure the food at the individual level. At the national level, food availability depends on internal food production, import, and aid in some cases. Therefore, the availability of food at the household level is a more appropriate measurement rather than a global or national level to monitor food security status. Food availability at the household level is often determined by their ability to produce or have the resources to purchase enough food.

National level food security

The estimation of National-level food security is a universal scale to compare between countries' food security performances. Food security at the national level is influenced by the factors that have an association with national food manufacture, food trade, and storage of food, which is essentially measuring elements of food availability. The survey to assess food security at the national level is conducted by various national and international agencies such as FAO, FEWSNET, IPC. The most commonly used metrics considered to evaluate food security at the national level are- global hunger index, Prevalence of undernourishment, and global food security index.

The prevalence of undernourishment (PoU) is a widely used metric that extracts national food supply and utilization data from the food balance sheets to calculate food availability at the national level [24]. PoU is the scale of choice by FAO to measure food insecurity.

Economist Intelligence Unit introduced the Global Food Security Index (GFSI) in 2012, a dynamic and quantitative benchmark that uses a set of indicators within three domains of food security: affordability, availability and quality, and safety. The overall goal of GFSI is to through the categories as mentioned earlier. In addition to assessing the metric, they also arrange countries based on their score, which shows the vulnerability of a country to food insecurity. Moreover, the parameter does measure not only food availability but also food access and diet quality [24].

The global hunger index was developed by IFPRI is another tool that allows us to monitor different parameters of hunger and undernutrition. Hunger is multidimensional. Therefore GHI focuses on four parameters, namely- Undernourishment, gross wasting, growth retardation, and mortality among the children. In addition to the metrics mentioned above [25]. Famine Early Warning Systems Network (FEWS NET) and Integrated Food Security Phase Classification (IPC) were also used to monitor and predict food security in the area with a high risk of severe food insecurity.

Household-level food security

The ultimate aim of food security is to ensure the food at a personal level demanding the necessity to check at the root level. The food might be adequate at the global or national level, but it might not render food availability at the individual level due to a broken link in the supply chain. A household is considered food secure when it has a year-round, physical, and economic access to adequate food for all its members need to maintain an active and healthy life. Food security can be achieved from their production or purchases to meet the dietary needs of all members of the household. It is also essential to mention the variants of household food insecurity- transitory and permanent food insecurity where the first one describes the seasonal unavailability and the latter used to imply sustained food scarcity. Household consumption and expenditure surveys (HCESs) are a practical tool developed by FAO, which is used to measure poverty, affordability, and socioeconomic status [26]. This aims to understand various aspects of consumption patterns, nutrient intake, diet quality, and diversity at the household level [27].

Food access:

To ensure food security, food must be available as well as accessible for the people. Food access is defined as having sufficient physical, social, and economic resources to procure appropriate household foods. This concept got the spotlight based on Amartya Sen's entitlement theory, where he mentioned four categories of the food source- production, trade, labor entitlement and inheritance, and transfer entitlemen [23]. The concept links food security with social, economic, and political parameters that are intricately interconnected and affect food security. Food access depends mainly on household purchasing power, therefore affected by socioeconomic parameters, such as- food market prices, incomes, expenditure, in achieving food security objectives. Here, Economic and physical access means that there is a sufficient supply of food that reaches the individual level. Affordability is a relative concept; the high price of food does not limit food access if the people have the resources to get their hands on—similarly, people with low-income face more significant challenges accessing food if the price hikes. Therefore, food access is a crucial component for the assessment of food security, but its measurement is more difficult to assess than availability due to its inherently multidimensional nature [22].

Utilization:

The concept of food utilization refers to the consumption and biological use of food, i.e., converting food to energy and various nutrients to meet their nutritional need. Sufficient energy and nutrient in the body are determined by proper processing, preparation, storage, allocation, and feeding practices within the household. Adequate food utilization is also associated with the diversity of the diet, clean water, sanitation, and health care to make the most out of the consumed food. This emphasizes the essential inputs of the factors that are not linked to food. Socioeconomic factors such as lack of knowledge can result in inadequate feeding practice; one good example is the use of replacement instead of breastfeeding even when it is available in newborns. People with chronic illnesses have higher energy requirements. Water-borne diseases, parasitic infections, and gastrointestinal illness can result in inadequate absorption of nutrients despite adequate food intake [28].

Stability:

The last component emphasizes stable and persistent access to food. A household can have adequate access to food for a certain period, which may be changed because of sudden shocks, such as- environmental disasters, political conflict, or economic challenges. Inadequate access to food periodically due to any of these factors is also considered as food insecurity. Hence, the stability concept refers to both the availability and access dimensions of food security [28].

2.2 Seasonal food insecurity

The notion of seasonal food security lies between chronic and transitory food insecurity. Here, the food shortage occurs recurrently for a definite period of the year, usually corresponding to the harvest of food crops. Although the problem is predictable and the factors responsible for seasonal food insecurity is also known. However, it is the most abundant form of food insecurity. The variation can be projected from before, implying that it is plausible to counteract by proper policy-making and implementation. All these data strongly suggest more studies in this field to ensure food security who need it most.

2.3 Studies that used system dynamics approach to assess food security

Food insecurity is a complex and multidimensional problem that is ideal to be studied using a system dynamics approach instead of traditional sectorial models. Such models can also be exploited to understand the interrelationship between multiple feedbacks between events and causations and point out the most prominent factors, allowing the evaluation of policies and their long-term influence. Considering all these advantages, there have been several studies that adopted a system dynamic approach to studying food insecurity that is listed in Table 1.

Authors	Emphasis
Bach et al. (1992). Food self-sufficiency in Vietnam: a search for a viable solution [29]	Studies potential solutions to self-sufficiency on food (supply) in Vietnam
Gohara et. al (2001), A System Dynamics Model for Estimation of Future World Food Production Capacity [30]	In-depth analysis of global food supply and demand
Bala & Hossain (2010), Modeling of food security and ecological footprint of coastal zone of Bangladesh. [31]	Illustrate feedback between food availability and ecological footprint. Besides, it emphasizes on sustainable development to increase food security

Kotir et. al, (2016), A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana [32]	Demonstrates the relationship between the population, water resource, and the agricultural production subsectors in West Africa
Guma et. al, (2016), Household food security policy analysis: A System dynamics perspective. [33]	Investigate food security challenges, and evaluate policies and intervention strategies for better livelihood at the household level
Amelia, Kopainsky, & Nyanga (2014), Exploratory model of conservation agriculture adoption and diffusion in Zambia: a dynamic perspective [34]	Studied various patterns, and identify coherent policy options to increase the implementation of conservation agriculture
Quinn et. al, (2002). Nation State Food Security: A Simulation of Food Production, Population Consumption, and Sustainable Development [35]	Model simulation linking food production, the requirements of the population consumption and sustainable development
Georgiadis et. al, (2005) A system dynamics modeling framework for the strategic supply chain management of food chains [36]	Analysis of the management of the food supply chain
Saeed et. al, (2000) Defining Developmental Problems for System Dynamics Modeling: An Experiential Learning Approach [37]	Application of system dynamics model to build a reference mode addressing the food security problem in Asia

Gerber et. al (2017), The Dynamics of Food Availability in sub-Saharan Africa An Endogenous Perspective on Food Production Systems [38]	Exploring the dynamic complexity of food availability in Zambia and implication of various policies

Table 1: Summary of the studies using system dynamic approaches

2.4 Seasonal small-scale farmer households food insecurity- the case study of Zambia

Zambia is a landlocked country located in south-central Africa and shares a border with Zimbabwe, Botswana to the south, Namibia to the southwest, and Angola to the West the Democratic Republic of Congo to the north and Tanzania to the northwest, and Malawi and Mozambique to the east. Zambia is divided into ten administrative provinces, which are subdivided into 117 districts, 156 constituencies, and 1,281 wards [39].

Zambia has a total population of 16.5 million, increasing at a rate of 3.0% annually. 64% of Zambians live in rural areas, which changes due to an urbanization trend among the young in recent years [39]. Rapid population growth increases fragmentation of the landholdings and smaller mean farm size and puts stress on the food access, especially for small-scale householders.

92% of the farmers in Zambia are small-scale householders who have to cultivate less than 5 hectares of land for growing food, and among them, 61.7% of the small scale farmer households cultivate less than 2 hectares of land [15, 40]. Ironically, small-scale farmers invest their blood and sweat to produce food but live in extreme poverty and experience food insecurity for the year (Fig. 4). The harvest from a small piece of land is neither enough to feed the people nor to provide enough money to purchase food or maintain a livelihood. The development of small householders is a crucial growth driver that can impact food security in many socioeconomic sectors in a positive direction [41].

Although copper and cobalt mining profoundly contributed to the Zambian economy, agriculture still plays a central role in the economy and food production. 70 % of the total Zambian population is involved in agriculture but contributes to only 12.6% of national GDP [12].

Several factors are responsible for the low yield agricultural system. Natural sources like rivers and rainfall are the primary source of water for agriculture. Zambian weather is humid subtropical in nature, which is characterized by rainfall as well as intermittent drought. On average, Zambia receives an annual rainfall of 700-1400 mm, which occurs during the rainy season from November to March [42]. Man-made climate change often leads to prolonged droughts, and ill-timed heavy rainfall affects detrimentally to the Maize harvest. Due to a lack of infrastructure, Zambian agriculture profoundly depends on natural factors, making the Maize production unpredictable and less productive. It does not allow multiple harvests in a year. Unfavorable climatic conditions also drive to the loss of livestock, which is also an integral part of their agriculture and food system. In recent years, the infamous El Niño phenomenon affected the sensitive Zambian food production increasing undernourishment rates [43]

Another essential element behind the food crisis is the lack of diversity in the food types among the Zambians. The main food staple is Maize that provides 60% of the country's caloric requirements, and it is accounted for 90% of the food production [7]. o understand the seasonal food insecurity in Zambia, it is important to look at the agricultural production season, which describes the seasonal variation of food availability. Figure 6 summarizes the annual production season of the main agricultural products in Zambia. The harvesting time of Maize is from April to June, which corresponds to the highest amount of stored food, which started to decline gradually in the following months. The amount of stored Maize is lowest from November till the start of the new harvesting season, which is called a lean season.

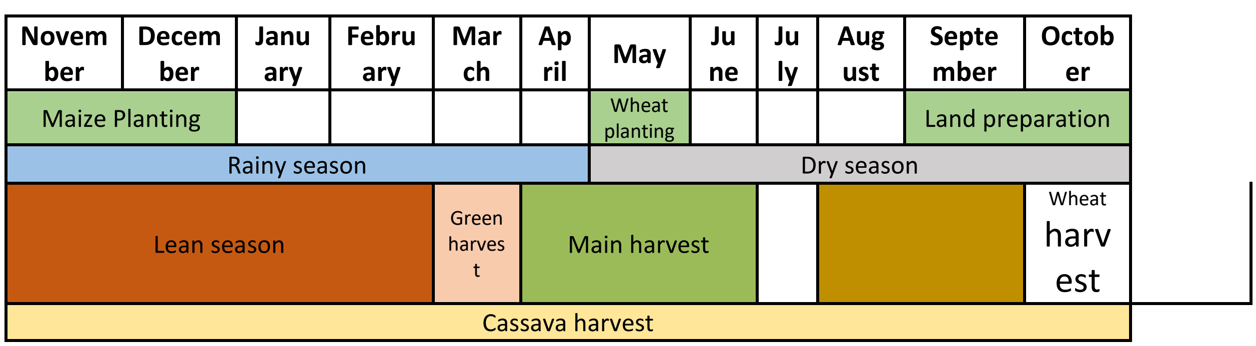


Fig 6: Overview of the seasonal calendar of main crops for a typical year in Zambia [8]

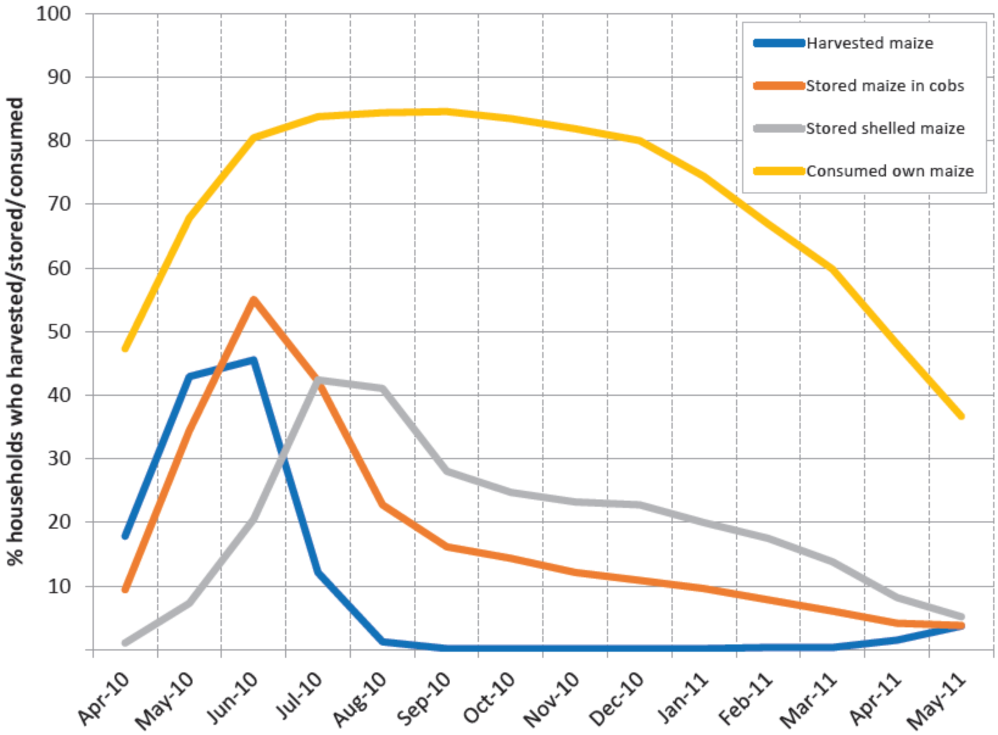


Fig 7: Harvest, storage, consumption, and purchase patterns in Zambia [44]

The farmers do not have access to quality seeds or modern, useful tools for cultivation, harvesting, and overall general agricultural techniques. Long-term mono-cropping of Maize and the use of chemical fertilizers deteriorate fertility and degrade the soil [10]. The absence of any alternative method for their income makes it more vulnerable to loss of resources such as land and the depletion of the livestock. Strengthening the economy is equally important as ensuring food security for the people, and it can reciprocally help the whole problem.

Several non-food factors are related to food insecurity. One factor like this is that the Zambian population is divided into more than 70 ethnic groups giving rise to long-standing tension among the tribes that eventually end up in a devastating conflict hindering economic growth [39]. Illiteracy, mistrust among the tribes, control over the natural resources play an essential role in giving rise to conflict, which takes a massive toll on its economy. This is often reported that one tribe group destroys the crops of the opponent group risking the food availability for a whole group for a year. The regions with geopolitical conflicts parenthetically match with the centers of undernourishment. Studies showed that the areas that are more likely to be affected by food insecurity are twice as high as in other regions in the presence of any unrest [45].

Food insecurity is the major underlying cause of malnutrition in Zambia. Only 36% of households in Zambia have enough food to eat, while 19% of households seldom or never have enough to eat, categorizing them as chronically food insecure [46]. Children and women more vulnerable to chronic food insecurity, resulting in an unhealthy future generation.

2.5 Agriculture land in Zambia

Zambia is a vast country with a total area of 752612 square kilometers. Over 50% of the total 39 million hectares of land are classified as the medium-to-highly fertile and suitable for crop production [47]. There is ample land, which possesses the immense potential to expand its agricultural sector and suffice the food demand. Despite having substantial agricultural potential, only 14 percent of this arable land is cultivated due to the use of the traditional agrarian method. Small-scale household farmers grow 1586334 ha of land, which is corresponding to 40% of the total arable area, implying that they are playing a crucial in meeting national food supply [48]. Zambia receives 40 percent of sub-Saharan natural water resources, drained through the Zambezi River, Victoria Falls, and Lake Kariba. Due to lack of infrastructure, very little mechanical irrigation detrimentally affects food production.

There are three broad categories of farmers: small-scale, medium, and large-scale. Small -scale farmers are generally subsistence producers of staple foods with an occasional marketable surplus. Most Zambians are subsistence farmers.

Farmer catagory	amount of land cultivate per farmer	Total area cultivated (percentage of total)	Number
Small-scale	less than 5 ha	1 586 334 ha (39%)	554 999
Emergent	5 to 20 ha	428 422 ha(11%)	49 700
Commercial	20 + ha	905 934 ha (22%)	1 980
Institutional	20 + ha	1 143 810 ha (28%)	2 516

Table 2: Land distribution among Zambian farmer [49]

29% of the small-scale householder cultivate only one hectare or less land, which is very small and unable to produce a surplus for sale. At the same time, it is less likely to earn sustainable incomes from cropping, unless substantial investments in productivity enhancement are made, and high-value crops are promoted [50].

2.6 Crop production by small scale farmer households

Zambia's agriculture is mainly dependent on rainfall, so crop production is vulnerable to severe weather changes. Notably, the small-scale farmers occupied themselves with the cultivation of food crops, whereas largescale farmers focus on producing cash crops. Almost all (90%) smallholders grow Maize as their main crop, where groundnuts are cultivated by 46%, and cassava is grown by 32% of small scale household farmers (fig 8). Other important food crops are soya beans, groundnuts, rice, wheat, sweet potato, and other vegetables and fruits. The most common cash crops are cotton, sugar cane, and tobacco tea and sunflower [51].

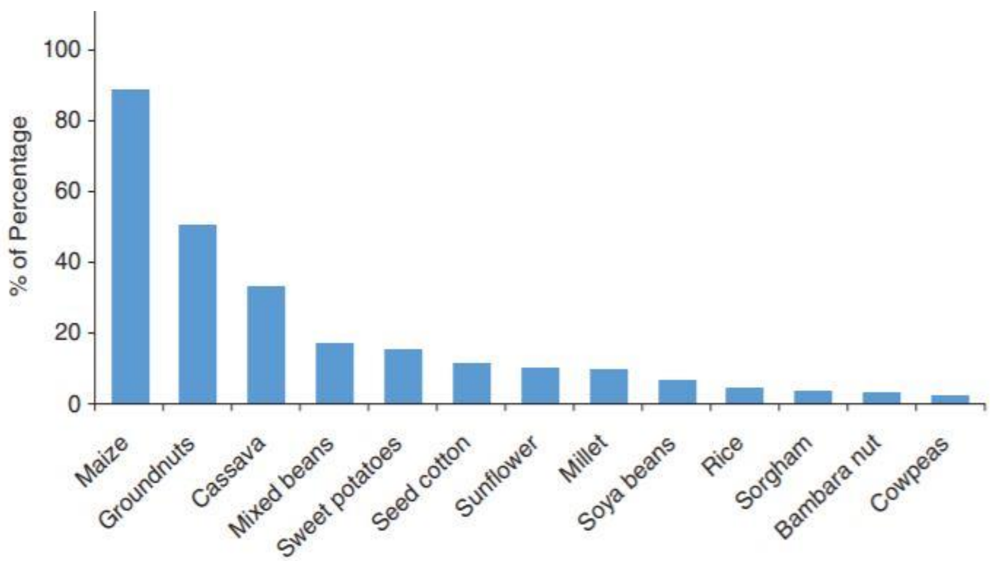


Fig 9: Main Crops produced by smallholder farmers in Zambia [15]

2.6.1 Maize production

Maize is the main food staple and the most valuable agricultural commodity in Zambia [52]. Zambia has a national Maize demand of approximately 2 million MT per annum. It is widely cultivated throughout the country by the 1.5 million smallholder farm households who account for 89% of total production [53]. Zambian population consumes approximately 105 kilograms of

Maize per capita annually in different forms. The national Maize production in Zambia was on the rise and had an annual Maize production of over 2.5 million MT since 2009, which was primarily attributed to an increase in the total harvested area over the years. Meanwhile, productivity increased barely from 1.32 MT per hectare to 2.10 MT per hectare (fig. 10). The area of Maize planted was doubled from about 750,000 hectares to 1.5 million hectares in the last decade. In the 2016/2017 season, Zambia produced a record amount of Maize of 3,606,549 MT, with a surplus of 1,178,516 MT [54]. They increased productivity by introducing better seed and adoption use of inorganic fertilizers and government subsidy programs. However, the course of increased production ceased was followed by a fluctuation in production, yield and harvested area in the last two consecutive seasons.

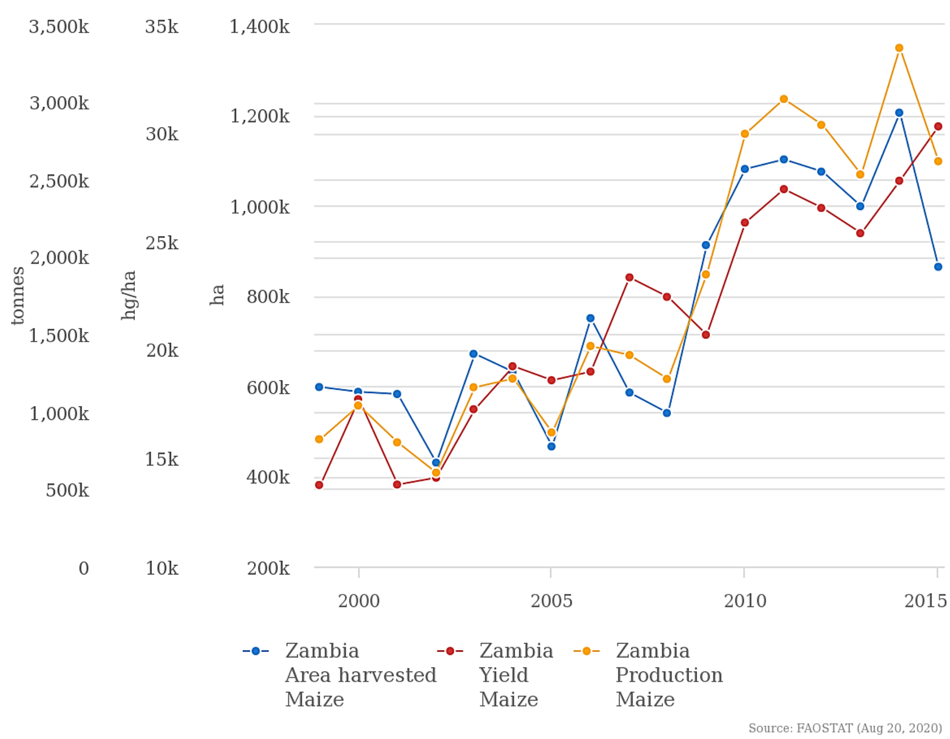


Figure 10: Maize production, planted area and yield from1999 to2015 [55]

2.6.2 Groundnuts:

Groundnuts are a popular food item throughout the world, consumed mainly as raw or processed to oil, peanut butter, and confectionary items. Zambian weather is ideal for growing groundnuts;

therefore is a significant producer to the world market. Groundnuts are the second-largest crop, after Maize, in terms of production volume and hectares cultivated. Approximately 8.8% of the total land cultivated in Zambia is planted to groundnuts [56]. The majority of this production is done exclusively by half of the 1.4 million small-scale growers using traditional cropping practices that result in low yields and low-grade products. Over the last five years, Zambia produced an average of 150,000 metric tons of shelled groundnuts. [49]. Despite favorable agro-ecological conditions and high commercial potential, it was not given similar importance as other crops. To unlock its commercial potential. The supply of improved groundnut seed, proper processing, and storage can lead to increased export markets.

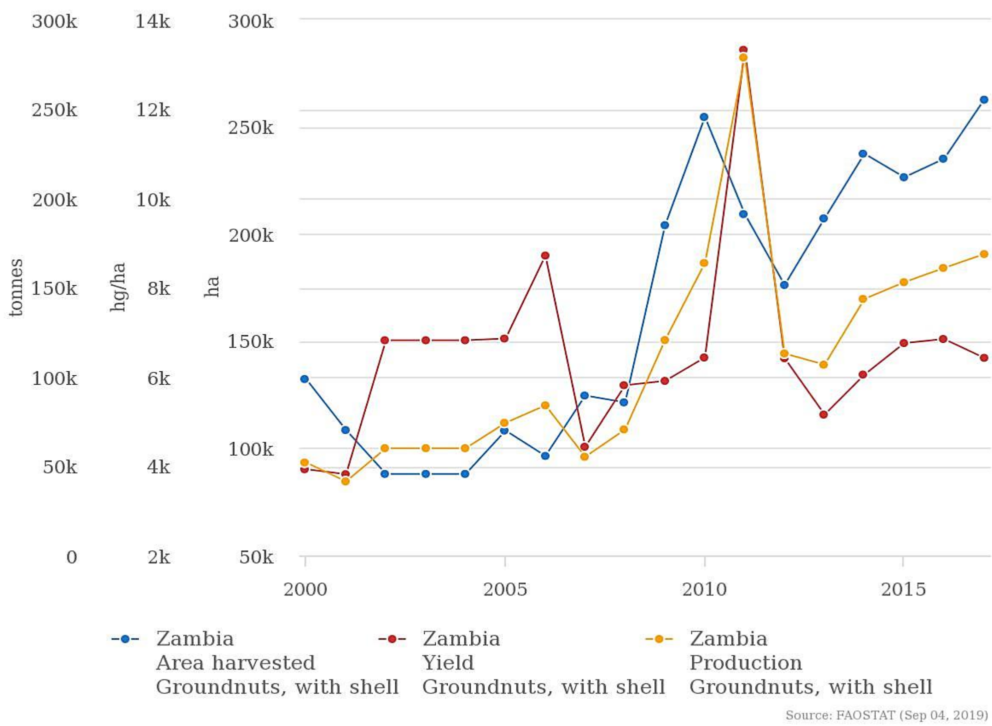


Fig 11: Harvested area and groundnuts yield over the years 2002-2016 [11]

2.6.3 Cassava

The tuber crop cassava is one of the main food carbohydrate sources in the tropical area of Zambia, which is especially consumed in the hungry season (Jan-Feb). This is one of the few significant crops in Zambia that is harvested all year round and not dependent on rainfall. Cassava farming is rapidly expanding among the small scale household farmers in Zambia. In 2017, it was widely grown by more than 500 000 small-scale farmers throughout the country with an annual production of 1.03 [49]. Cassava is consumed as fresh or dried as flour. Besides its use as food, Cassava is also a significant source of biofuel, which can reduce oil import and contribute to the economy of the country.

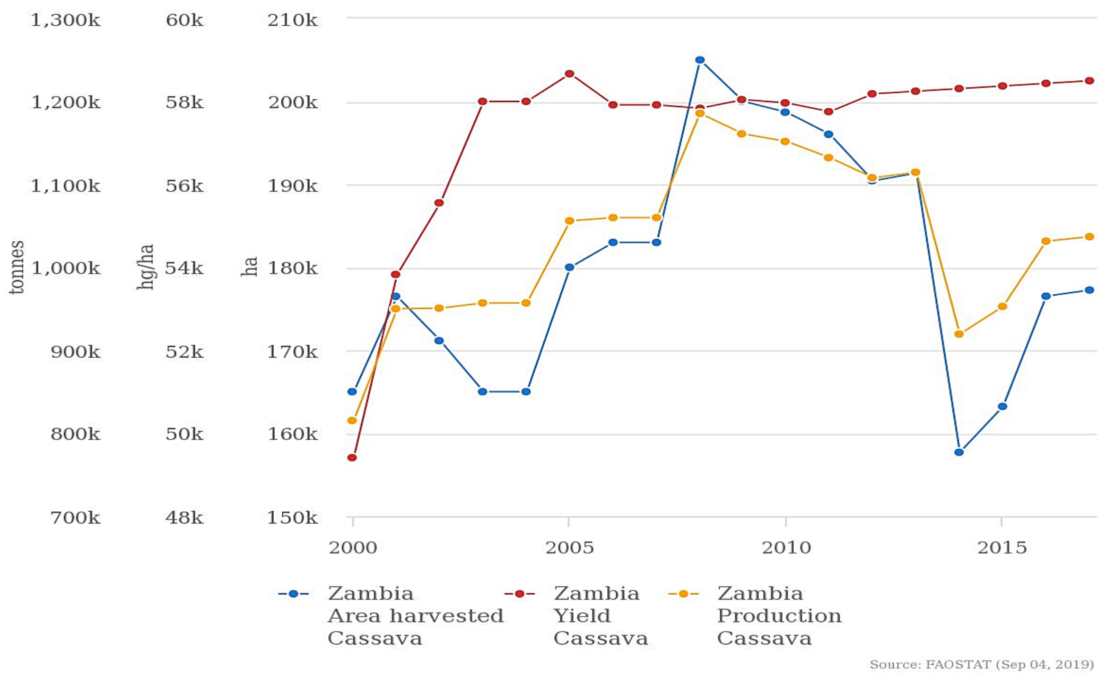


Figure 12: Trends in Zambia Cassava production and total area planted [11]

2.6.4 Mixed beans

Zambian farmers are encouraged to diversify their selection of crops of harvest, making mixed beans one of the main food crops in Zambia. Mixed beans are classified as food legumes, that can increase soil fertility. Being a less input crop, mixed beans are ideal for growing by the small scale household farmers. Moreover, they have the potential to provide high yield and serve as an important cash crop. Figure 13 shows that the area of mixed beans harvested and expected production fluctuated slightly in Zambia. In 2018, mixed beans were harvested in 65,200 ha with a total production of 31752 MT [11].

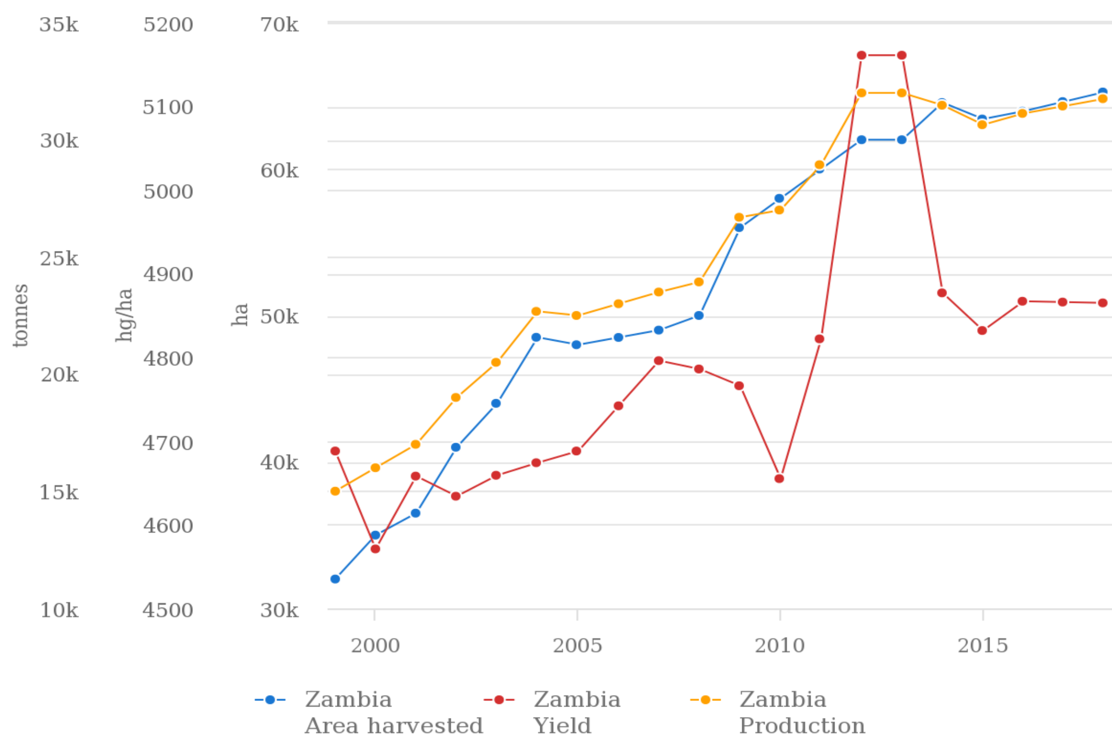


Figure 13: Trends in Zambia mixed beans total area harvested and expected production [57]

2.6.5 Agriculture input and Subsidies

The Zambian government has taken several policies through various strategic plans to improve agricultural outcomes. As a part of that, fertilizer subsidies were started as a part of the policy agenda since the 1990s. The country spends 90% of its agricultural budget on subsidies to stimulate private sector participation as a part of Poverty Reduction Programmes (PRPs) [58]. These are fertilizer and seed subsidies through the implementation of the Farmer Input Support Programme (FISP) and the purchase of grain at an above market price by the state-run Food Reserve Agency (FRA); Zambia's fertilizer consumption increased since its introduction. In 2016 fertilizer consumption was 89.59 kg per hectare of arable land in comparison to 25.68 in 2006. 77 percent of the fertilizer is applied to Maize by small scale household farmers, which they get through FISP. Formerly known as the Farmer Support Programme (FSP), FISP was introduced in which was reformed to become the FISP with the adoption of the goal of increasing household food security and incomes in 2009/2010 [59]

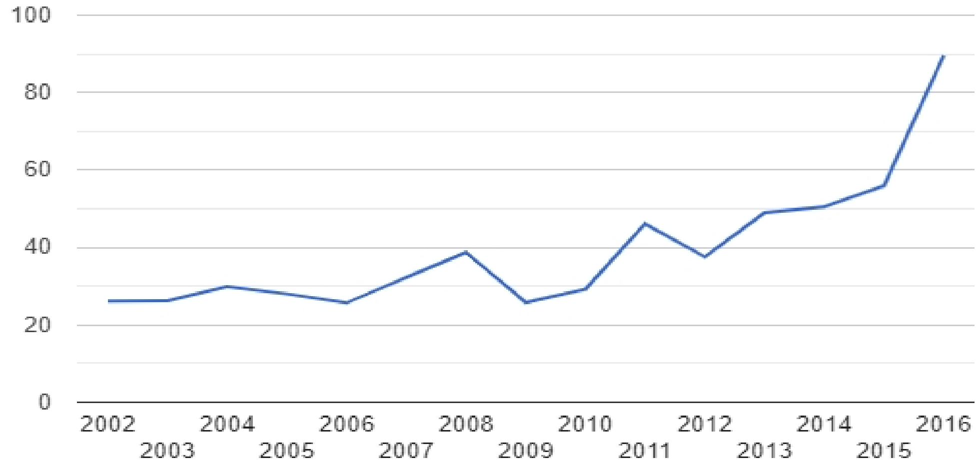


Fig 14: Use of fertilizer in Zambia per hectare of arable land [60]

Despite the FISP initiative, the share of small scale householders with fertilizer use is only 39 percent in 2010 (Table 9). However, the program was evolved in a positive direction, increasing the number of beneficiaries and the inclusion of other crops. An average of 180 000 MT of fertilizer was distributed through FISP each year between 2010/11 and 2012/2013 [58]. On average, each household gets a package of 200 kg of fertilizer and 10 kg of hybrid Maize seed [61]. The distribution of these subsidies is often carried out disproportionately, which is affecting the output of the program FISP.

	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10
Central	35.59	48.01	39.17	42.12	39.20	47.00	56.53	50.41	66.18
Copperbelt	31.73	33.97	36.61	39.06	42.52	46.54	46.14	44.61	58.06
Eastern	22.01	28.31	30.11	32.16	30.64	26.74	31.25	29.01	42.54
Luapula	10.20	14.29	12.79	7.57	11.28	14.38	12.16	14.00	16.45
Lusaka	34.16	51.60	65.75	64.40	55.57	49.27	52.09	48.20	69.07
Northern	18.74	22.42	21.09	20.32	21.41	35.87	31.44	30.93	37.34
Northwestern	11.79	10.73	18.08	11.56	18.49	21.73	18.59	18.26	30.34
Southern	26.30	40.50	38.64	27.93	25.96	33.42	36.78	33.47	41.33
Western	2.98	9.48	4.88	4.49	5.58	5.05	3.09	3.96	7.62
National	19.99	26.78	26.27	24.54	24.94	29.29	30.24	28.86	38.79

Table 3: Percentage of smallholders using fertilizer in different zones of Zambia [62]

The literature review provided an insight into the core concept of food security, background about Zambia and the problem of food insecurity among small-scale household farmers. It also included the status of main agricultural production. In addition, it offered the knowledge of the severity and importance of the problem, which motivates me to contribute to solve the food insecurity among small scale household farmers. The literature review created the foundation, determine the purpose for the study and made the model boundary.

3 Research Methodology and Strategy

3.1 Research Strategy and Methodology Choice

Understanding the behavior and structure of a complex system- such as the household level food insecurity- can only be accomplished through an integrated approach instead of studying individually. System dynamics approach allows studying the dynamic relationship between multiple factors at a time. It integrates them into a computer simulation to find out the endogenous drivers of the system and formulate a reasonable policy [63] [64]. This approach is tailor-made to analyze complex systems like food production systems by representing the interplay between subsystems. That's why system dynamics (SD) has been chosen as the method for analysis in this study.

In this study, the well-established framework for System Dynamics modeling projects by Sterman [64] will be followed, which is composed of developing a conceptual framework, data collection and analysis, model building, and design policies based on the findings. The foundation of a model is laid on the development of a conceptual structure illustrating the relationships among the variables. This preliminary structure is called a causal loop diagram (CLD), which is created based on the findings of previous researches on the same theme.

My current study relies on the case study of smallholder farmers in Zambia by Andreas Gerber, where he built a simulation model at the national level to investigate the potential of a fertilizer subsidy program to improve Maize production in Zambia [38]. Additionally, the structure allowed me to focus on food security at the household level, instead of national-level Maize production.

My thesis consists of the exploratory, descriptive and explanatory components. The exploratory part illustrates the nature of the problem in-depth, by putting relevant data together and finding out the key elements that can be maneuvered to improve the seasonal food availability among small-scale farmer households. This is followed by the descriptive part, which outlines various aspects of food insecurity in the form of a quantified SD model. Following the agile SD principles, iterative cycles of data collection, model building, simulation, analysis, validation, and documentation were performed throughout the project [64] [65]. The outcome of the model was further revised and tested in parallel as the iterative cycles were forwarded to improve efficiency.

3.2 Data Collection and analysis

3.2.1 Data collection

The data that we used to build, test, validate the SD model for addressing the research questions can be divided into two groups:

• The structural components are the factors that contribute to Maize production and seasonal food shortage among small-scale householders in Zambia. This also encompasses stock, flow and exogenous variables, causal relationships, and formulas that address the relationships between variables.

• Time series data incorporates the known modes of behavior over time and parameter data for exogenous variables.

Data that are applied in the SD varies according to the sources, such as documented numerical data, documented written data, and assumptive data present obtained from the previously performed research studies [66]. In my current study, it was not possible for me to travel to Zambia in person for first-hand data collection. Due to a lack of updated information in several instances, the study relied upon secondary data and academic literature.

To organize the secondary data and literature, the purposive sampling method was adopted. Particularly, a critical and heterogeneous sampling was used to build my research on relevant secondary data and literature. In my model, a wide range of reliable sources was collected from various sources and scrutinized to avoid biases, increase reliability, and improve the quality of the research outcome.

The quantitative data that was required to construct the model was mainly obtained from databases of public institutions like the FAO, the world bank and the central statistical office of Zambia. In addition, time-series data were adopted from various research papers, especially publications by the Indaba Agricultural Policy Research Institute (IAPRI).

The qualitative data that was essential to establish the foundation of the research was taken from academic literature, reports of organizations such as USAID or UN agencies. Notably, reports from IAPRI and the FSRP provided very specific, elaborated and useful data. Nevertheless, these resources could not provide some necessary data that was needed to build the information feedback structure of my model.

3.2.2 Data analysis

Formal model analysis and validation were performed through various tests, i.e. direct structure tests, indirect structure-oriented tests, and behavior tests that allow quality control and build confidence in the model [67] [64]. The aim of the model analysis and validation was to:

1. Evaluate the model to address the research questions.

2. To obtain a deeper understanding of the model behavior; and,

3. Identify leverage points and challenges in the food production system to improve system behavior

The data were analyzed using the structure confirmation test; we scrutinized variables, and the causal relationships between them, impacting Maize availability stock. On the other hand, qualitative behavior reproduction tests were performed to match the outputs of partial model tests with patterns of observed reference modes [67]. The outputs of all validation tests were applied for interpreting internally generated model outputs to address the research questions.

4 Model description

To study the dynamics of food insecurity among the small-scale farmer households in Zambia, a model was created using the system dynamics approach. In this chapter, we explained the model structure of the food insecurity system as a whole and in-depth exploration of the individual modules. Lastly, the overall integrated structure of the model will be described illustrating how the subdivisions interact with each other from a feedback loop perspective.

The model structure describes the outcomes illustrated through stocks, flows, and independent variables and the short and long-term effects rooted in every system. This structure provides quantitative and qualitative components of the system on which behavior is outlined to illustrate the system. The qualitative aspect of the system is delineated by the causal linking of variables and its quantitative element is represented by the formal definition of these causal links through equations [68]. Sterman demonstrated a thorough explanation of the basic structure and building blocks of the system dynamics methodology [64].

4.1 Model Overview

This section outlines the different sectors used in the model. The model was created with Stella Architect software (V2.0) that emphasizes understanding the dynamics of the seasonal Maize productions and consumption pattern, availability of food throughout the year, soil dynamics, and agricultural land use among small-scale farmer households Zambia.

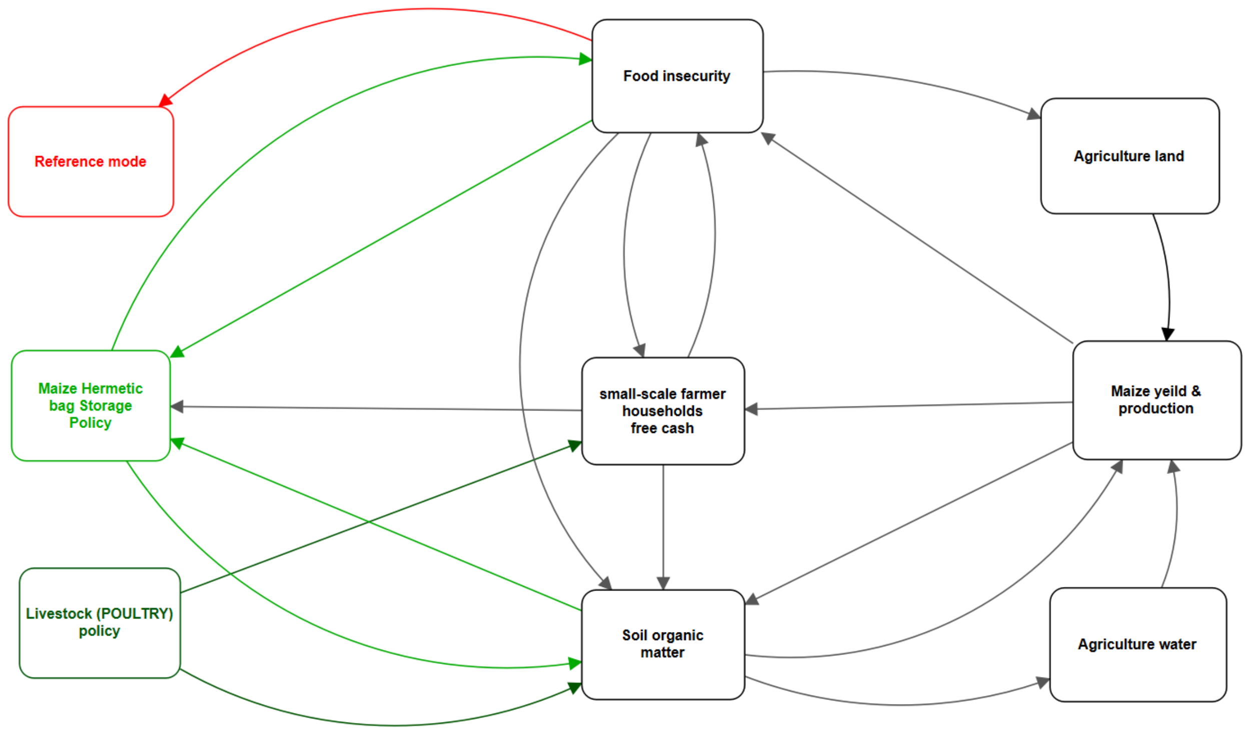


Figure 15: Small-scale farmer households food insecurity model overview

Figure 15 shows a simplified version of the model structure illustrating the feedback relationships among the modules food insecurity, agriculture land, Maize production & yield, agriculture water, soil organic matter, and small scale farmer household free cash. Most of the modules are affected by several other modules and influence multiple modules. For example, the Maize production & yield module is influenced by the other modules such as soil organic matter, agriculture water, and agriculture land. Likewise, Soil organic matter and small-scale farmer households free cash are highly dependent on the Maize production and Maize yield.

The model is divided into sectors, portraying the main dynamics of the system. Each sector encompasses modules that form the structure showing the dynamics. The modules are interrelated with each other, with variables affecting the entirety of the system that will be elaborated in the following section.

To eliminate the problematic behavior of the system, several leverage options structures were intervented in the model, such as- livestock (poultry), farmer's access to more fertilizer, conservation agriculture and zero post-harvest loss was described in policy analysis sector (Chapter 6).

4.2 Stock and Flow Structure

This section demonstrates the model structure on the dynamic problem of the household's food insecurity. Model structure can be defined as the arrangement of stocks and flows, and auxiliary variables used to represent any system. Model structure characterizes the system's qualitative and quantitative dimensions through the causal linking of variables and integrated equations between them. Stocks are defined as variables, which are accumulated over time, and are symbolized by rectangles. Flows, on the other hand, are the variables influencing stocks, through which accumulation or depletion of stocks occur. Stocks accumulate (integrate) their inflows less their outflows, and are represented by arrows and valve symbols [69].

Thus, a stock and flow map resembles a system of integral or differential equations. Stocks and flows can be identified by the units of measure. When a stock in a system is measured in units, its flows must be measured in units per time. Auxiliary variables are used to demonstrate external parameters or intermediate steps between stocks and flows or add conceptual clarity to the model [70] [64].

In this study, the model is subdivided into several modules; that contains a set of stock and flow structure in the areas of population scenario, land use for Maize production, soil organic matter, fertilizer subsidies, small-scale farmer household free cash, agriculture water, food insecurity, and Maize production & yield. Due to space constraints, the whole structure could not be explained at once. Instead, the specific structure of the model is elaborated together with the explanation. The stocks and flows are connected by feedback links with several differentials and algebraic equations based on factual or admissible empirical data [71]. In the current study, the model structure elucidates the relationship between food production and the frequency of food shortage among small-scale farmer household populations in Zambia. Estimated values of the variables, equations, units, reference, and general notes of some formulations, are stated in the Appendix.

4.2.1 Sub-model Description

In this chapter, we will describe the structure of each sub-sector in the model in terms of stock and flows with main formulations.

4.2.1.1 Maize yield and Production sector

Agriculture production and yield depend on the use of arable land, and availability of other agricultural conditions such as water, fertilizers to improve soil fertility, and the use of pesticides. The amount of Maize production is directly proportional to the area of the cultivated land and the fertility of the land, depending on the variables mentioned above. In this section, we will focus on the dynamics of land use and its fertility to explain the dynamics of food production.

The yield and production sector has two subsectors, one representing the determinants of yield (nutrient and water uptake) and the other illustrating the effect of nutrient availability on yield. Here, the variable “yield” is used to represent the number of crops harvested per hectare (MT/ha). The availability of water and nitrogen is the most important limiting factor for poor yield [72, 73]. Nitrogen can be supplemented by using fertilizer, indicated by the variable “fertilizer application per hectare,” and the natural mineralization process mentioned as the variable “nitrogen mineralization rate” (details in section 4.2.1.1.1). Even though crop residues are beneficial, farmers often use them as livestock feeding or burn them to clear the field [73]. The availability of water depends on irrigation and Soil organic matter that affects the water-holding ability of the soil. Zambian agriculture is mostly rain-fed due to minimal irrigation facilities available [74].

Figure 16 depicts that the Maize yield is calculated by a production function based on the availability of water and nitrogen uptake. Here, the Maize production is calculated using the seasonal counter to show the strong seasonal effect on food production in Zambia. Later, the production is obtained by multiplying yield by the area allocated for Maize to the Small-scale farmer households.

The equation of the maize productions are given below:

Seasonal_maize_production = IF Seasonal_counter>=4 AND Seasonal_counter<5 THEN
(Main_harvest_yield*Share_of_April_harvest*Maize_harvested_area) ELSE IF
Seasonal_counter>=5 AND Seasonal_counter<6 THEN
(Maize_harvested_area*Main_harvest_yield*Share_of_May_harvest) ELSE IF

Seasonal_counter>=6 AND Seasonal_counter<7 THEN (Main_harvest_yield*Maize_harvested_area*Share_of_June_harvest) ELSE IF Seasonal_counter>=7 AND Seasonal_counter <8 THEN(Main_harvest_yield*Share_of_July_harvest*Maize_harvested_area) ELSE (Share_of_others_time*Main_harvest_yield*Maize_harvested_area)

UNITS: ton/month

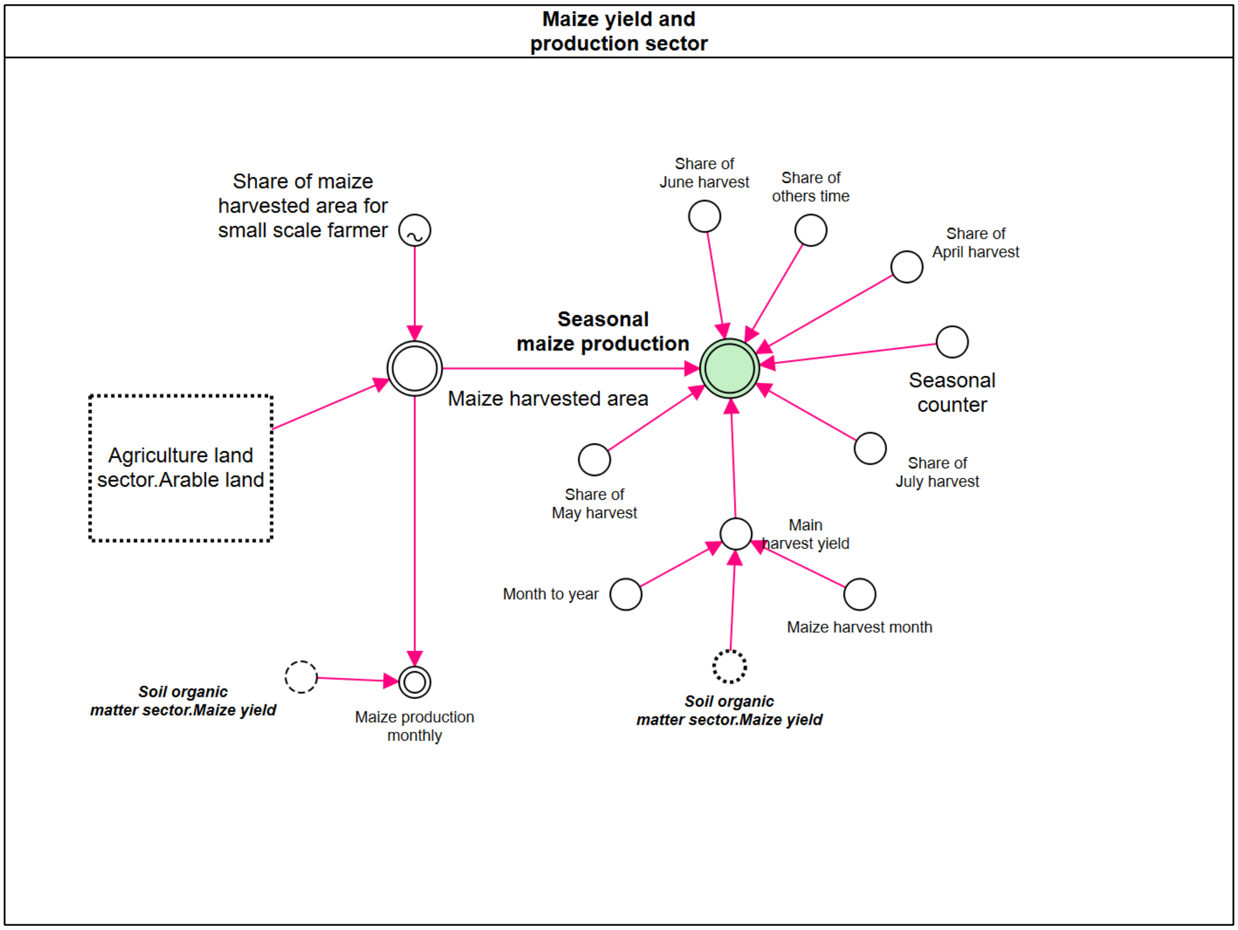


Figure 16: Stock and flow structure of Maize yield and production sector.

4.2.1.2 Soil organic matter sector

Soil Organic Matter (SOM) is an essential determinant for soil fertility that affects Maize production. Here, we show the soil dynamic through the stock and flow structure.

Figure 17 demonstrates the stock soil organic matter has an inflow named SOM input to the soil, which is affected by the remaining plant residues on the field and nutrients coming from the livestock manures. The Maize plant is a by-product of Maize production; farmers leave them on the field while harvesting. Nitrogen in the crop residues converted into soil organic carbon and thus turned to SOM. This improves the structure, water holding capacity, and overall fertility of the soil resulting in enhanced plant growth and harvest [75, 76]. During this, the biomass, referred to as the organic material in the area that comes from the plants, does not change. The outflow of SOM stock is the mineralization rate that implies the slow release of organic nutrients to be taken up by the Maize plants. Mineralization is a biological process that occurs over a long period, which rates vary with soil temperature, moisture, and the amount of oxygen in the soil [77]. The nitrogen content in the residual plants is converted to soil organic nitrogen by the soil bacteria, restoring nitrogen reserve in the soil in the next growing seasons. During this, the nutrients advance from the SOM pool to the available nutrients pool to be uptaken by the plant. In our model, the SOM mineralization period is 30 years (360 months) to deplete the SOM nutrients.

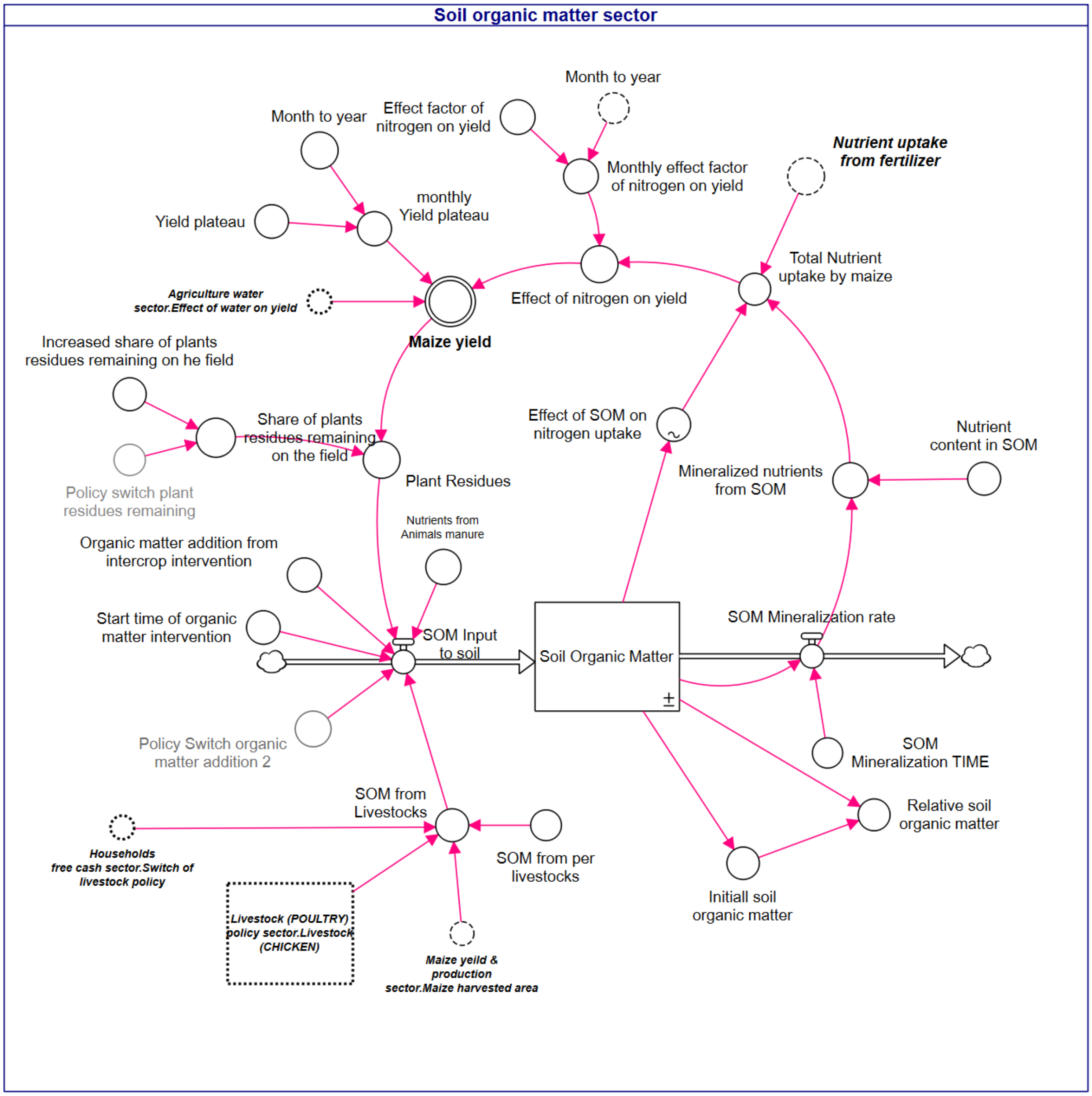


Figure 17: Stock and flow structure of Soil Organic Matter

4.2.1.3 Fertilizer sectors:

Fertilizer application is crucial to soil quality and crop production [78] [79]. Proper use of fertilizer improves soil nutrient availability that eventually boosts crop harvest Government subsidies are not sufficient; therefore, farmers buy fertilizers with their revenue. Fertilizer application is enhanced by increasing the number of received subsidies and private fertilizer expenditure [80]. On the other hand, fertilizer application is hindered by an increase in fertilizer prices. Small-scale household farmers in Zambia make use of 90% of agriculture cost that is used to purchase fertilizer and soil development in addition to their subsidies from the government (fig. 18). [81]

The efficiency of fertilizer application and soil enrichment is calculated by the total fertilizer expenditure, fertilizer price, and total Maize harvested area. We determined the number of nutrients from the fertilizers, using the following formula:

Nutrient uptake from chemical fertilizer =

(Total_fertilizer_Expenditure/_Fertilizer_price/ small scale farmer Maize harvest area)

From the equation, we get the number of required nutrients for the total land area by dividing the total fertilizer expenditure by the per-unit fertilizer price. Then, we determined the actual amount of nutrients if necessary per hectares per month by dividing this total amount of nutrients with Maize harvested area.

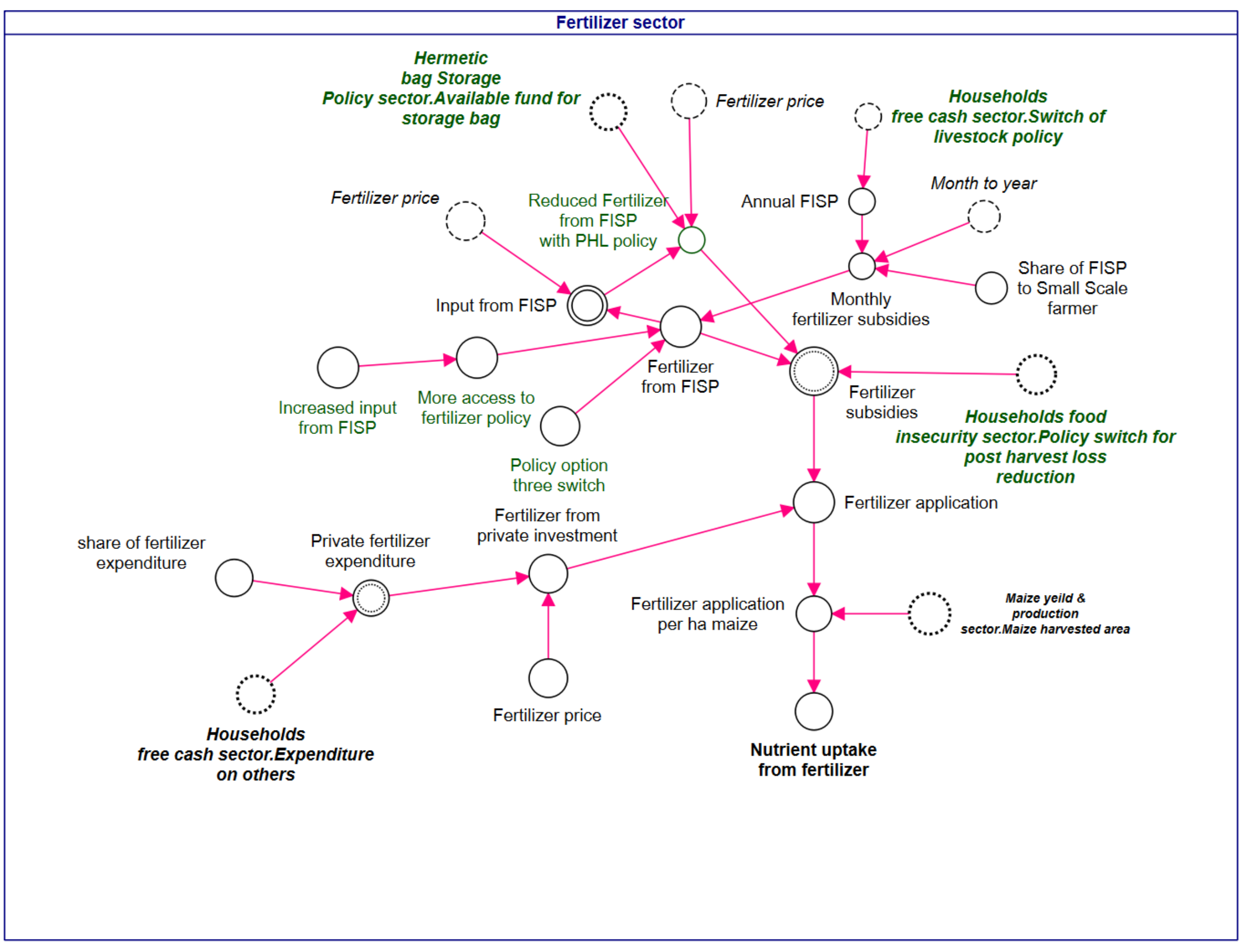


Figure 18: Stock and flow structure of the fertilizer sector.

4.2.1.4 Agriculture Water availability sector

The availability of water is an important growth factor for Maize plants. Rainfall accounts for the only source of irrigation in 95% of the arable land, and constitute 90% of staple food production in sub-Saharan Africa [74] [82]. Rainfall occurs unevenly throughout the country and only during the rainy season (November to April). Due to the lack of man-made irrigation systems, this precipitation pattern allows only one Maize harvest per year.

Fig 19 shows the entire share of water used in the production of Maize derived from annual precipitation. In the model, we set the average yearly rainfall in Zambia as 1 020 mm [83].

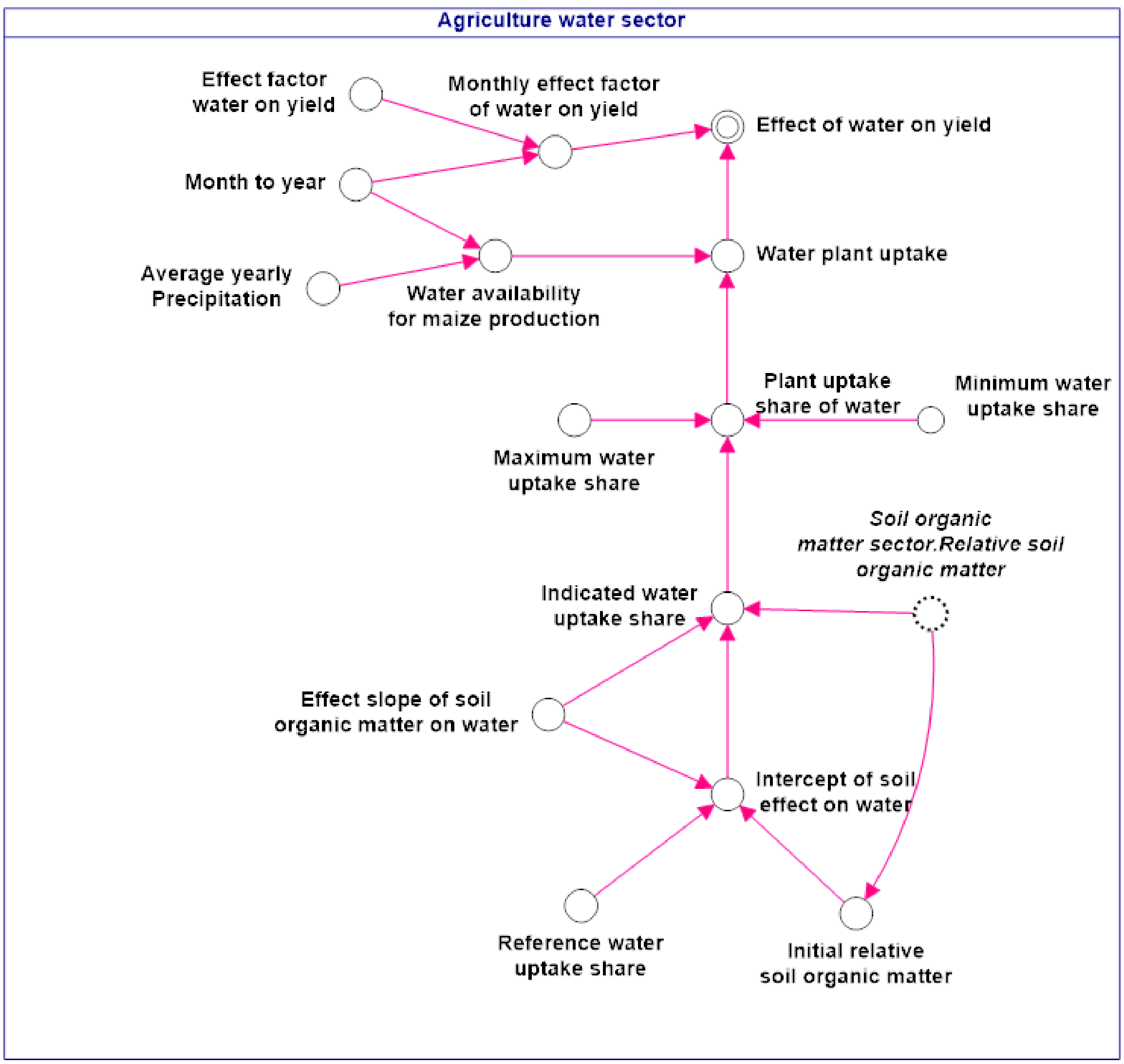


Figure 19: Stock and flow structure of agriculture water sector

4.2.1.5 Agriculture land-use dynamics sector:

The land is the most critical element for food production. In the model, the land module shows the internal processes of how potentially arable land turns into arable land to reduce the gap between food demand and food availability of the population.

At first, the food deficit is achieved by subtracting Maize availability from the Maize demand. Hence, the arable land demand is influenced by the supply-demand balance and the population growth rate. In the case of food oversupply, the need for arable land decreases, and it is valid for the other way around. It takes 48 months (time to arable land conversion) to adjust arable land demand from calculating the difference between the arable land and arable land demand. The stock of arable land increases the area of potentially arable land for food production (fig. 20).

Following equation is used to calculate the change in arable land:

Change in arable land conversion rate=MIN(MIN(Arable_demand/Arable_land_conversion_time, Maximum_arable_land_demand/Arable_land_conversion_time)-
Arable_land/Arable_land_conversion_time,
Potential_arable_land/Arable_land_conversion_time.

This variable depicts the exact change derived from the conversion of potentially arable land into arable land. Here, the primary inducer is the arable land demand. The transformation of arable land can be hampered by a reduction in the potentially arable land or decrease in government subsidies to agriculture.

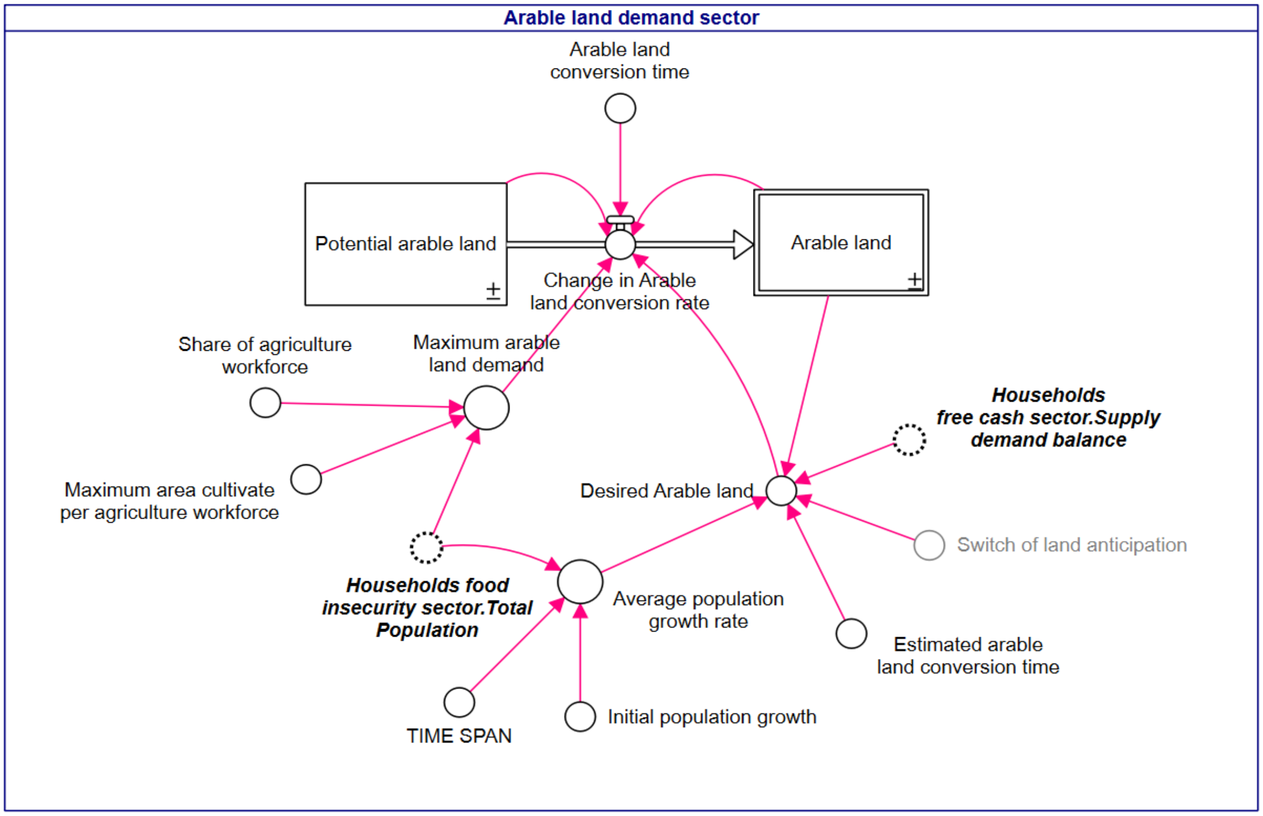


Figure 20: Stock and flow of agriculture land sector.

4.2.1.6 Small scale farmer households free cash and expenditure sector

The following chart depicts the flow of free cash and their expenditure among the small-scale farmer households in Zambia. The small-scale household farmers do agriculture as the main economic activity. From figure 21, we can see that farmers utilized their produced Maize for consumption and sell a part of that to make money for livelihood. Hence, Maize serves as their main cash crop and provides its net income. The average market price and the number of crops sold determine the availability of net household free cash. In Zambia, small scale farmers spend around 60% of their income are used to purchase food. The rest serves different purposes, including expenditure in fertilizer and soil improvement [47]. This investment in the production of food for the next year is a dilemma to the farmers as more expenditure does not bring the proportionate harvest, which can reduce the profit margin.

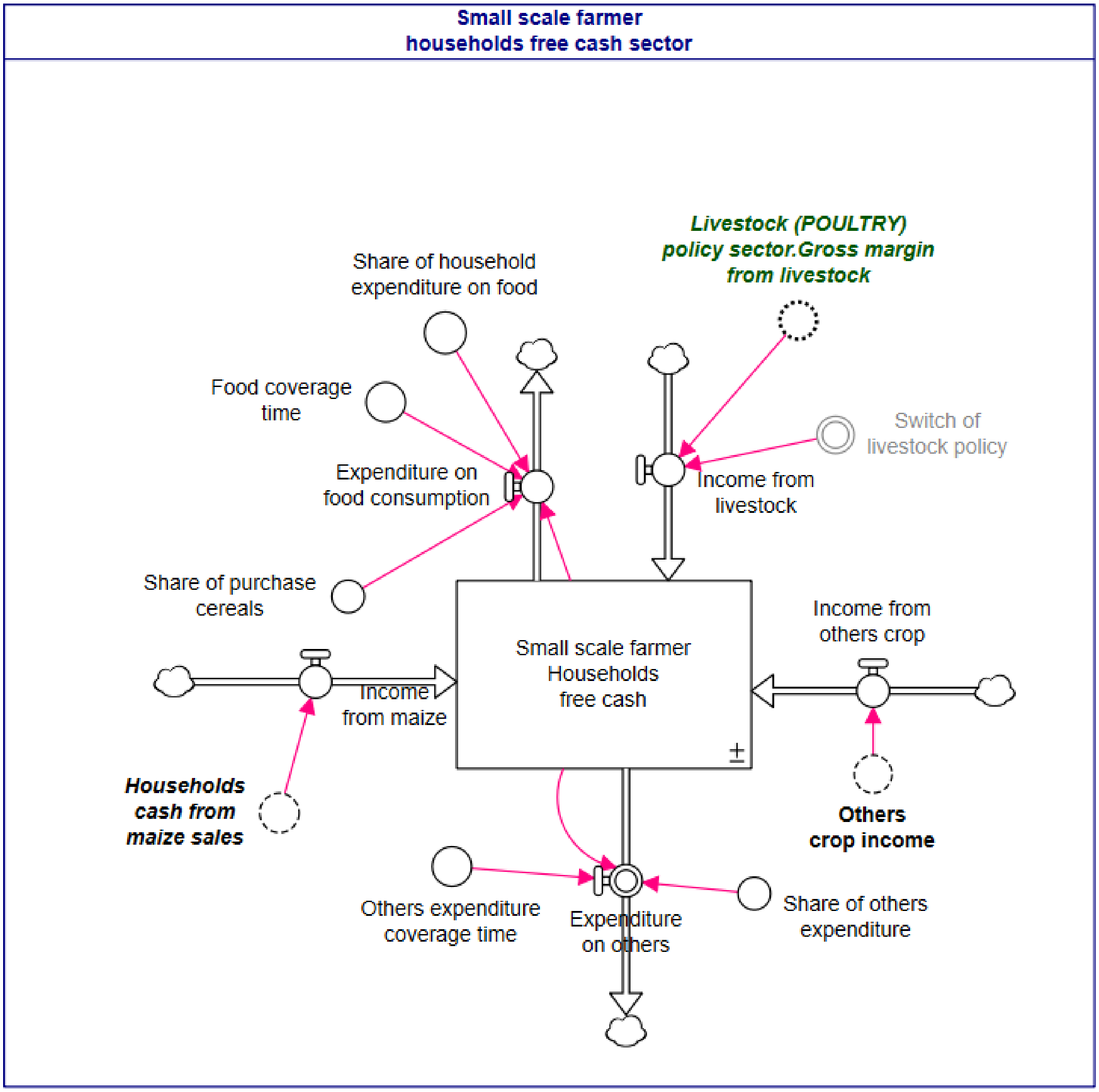


Figure 21: Stock and flow structure of household free cash and expenditure sector.

4.2.1.7 Maize sales and Maize market price sector:

Most of the crops produced by the Zambian farmers are used for food, and the rest is used for livelihood [84]. Approximately 28% of smallholders produce more Maize than they need, who can sell them to make money. Around half of the Zambian smallholders have to buy more Maize than they sell, and 23% do not buy or sell Maize [47]. Agriculture is the primary economic activity in Zambia, but livestock and handcraft objects by household members contribute to the household free cash [85]. The household cash generated from selling from the Maize is determined by the price and the quantity of Maize sold. The price of Maize varies at different times of the year. It follows the supply-demand ratio principle, implying low Maize price during high supply in the harvesting season (May and June) and increased Maize price in the lean season due to low supply (December to March). Net sellers can profit from hiking Maize prices, but the poor small scale householders are affected in the lean season when they are economically vulnerable (fig. 22).

We calculate the producer Maize price by the following equation in this sector:

Producer_price_Maize_real = effect_of_supply_and_demand_on_producer_price*Reference_producer_Maize_price_real

UNITS: kwacha/kg

Thus, higher Maize prices affect nearly half of the smallholders who buy Maize. The large-scale farmers and a fraction of smallholders who do not sell crops are the got advantage of higher Maize prices.

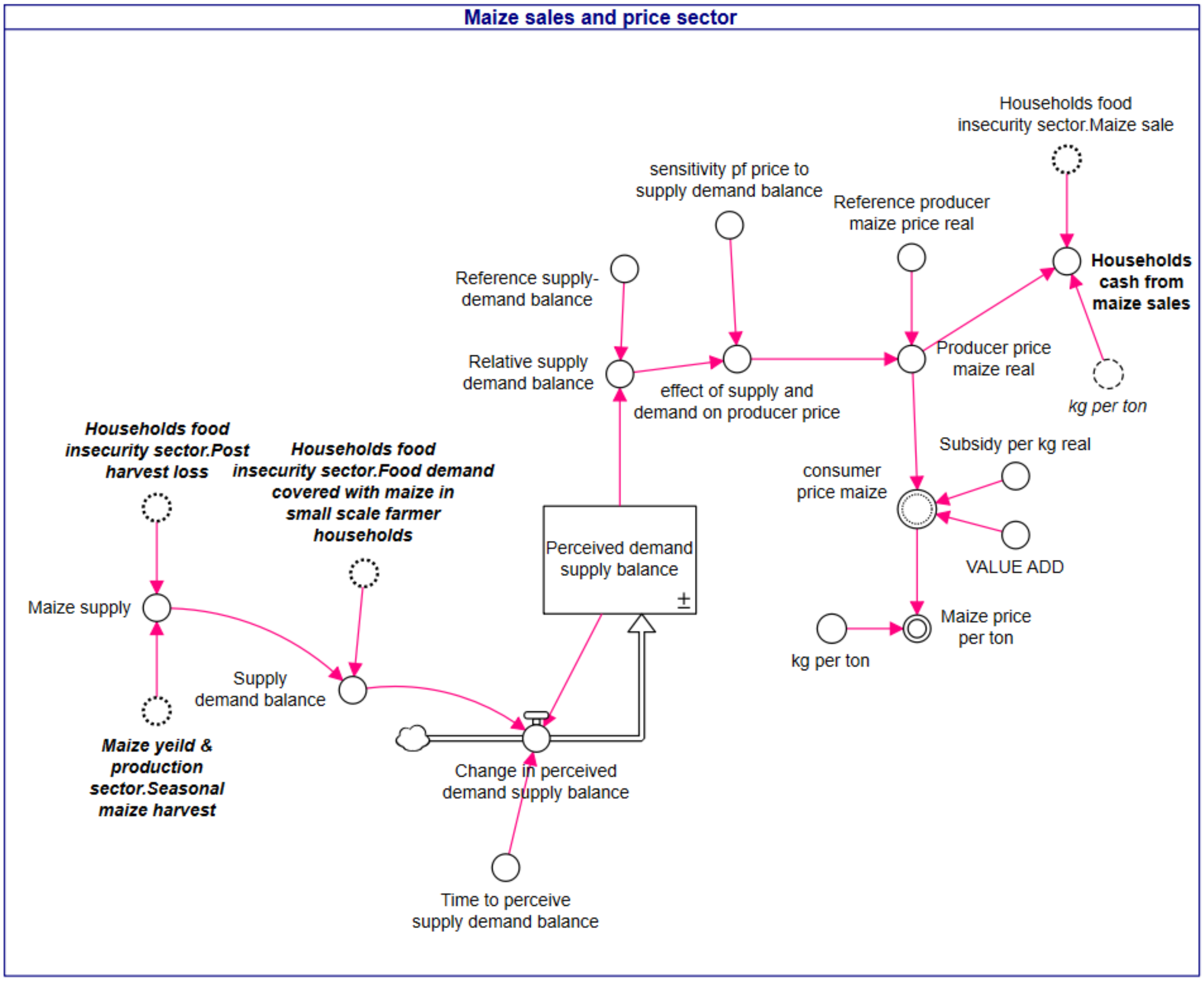


Figure 22: Stock and flow structure of the Maize price sector

4.2.1.8 Income from other crop sectors:

92% of Zambian farmers are small householders who cultivate fewer than 5 hectares [40]. Almost all smallholders grow Maize, which is the main staple, and they make up 90% of total Maize production [15]. While Maize, Cassava, and sweet potatoes are grown for food security, cotton, soybean, tea, tobacco, groundnut, are grown as cash crops [51]. Production of Maize is heavily dependent on rainfall, allowing it to grow only once in a year. Therefore, there is a need for variation in choosing crops for cultivation. This will allow alternative food crops with multiple harvests and reduce the vulnerability to food insecurity due to the poor harvest of Maize. .

In this subsector, we used the exogenous variables to calculate the income from other major crops harvest by small scale farmer using the following equation-

Others crop_income =

Income_from_cassava+Income_from_Groundnuts+Income_from_mixed_beans

UNITS: kwacha/month

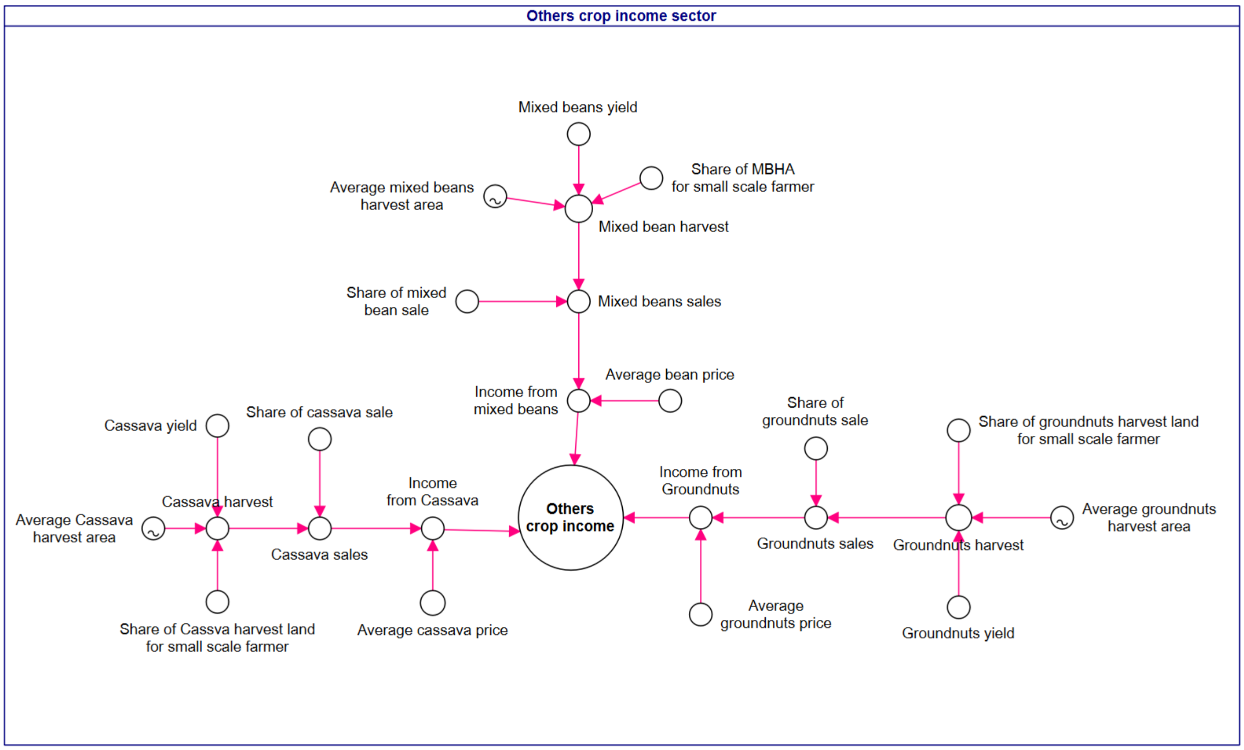


Fig 23: Stock and flow structure of income from other crops sector

4.2.1.9 Food insecurity sector

This section refers to the indicators to assess food insecurity among small scale farmer households based on the prevalence of undernourishment and food deficit, which was calculated from the kilocalories consumption from main staple food.

4.2.1.9.1 Food availability sector:

This segment describes Maize availability with regard to Maize storage, Maize consumption, and Maize purchase ability. The Maize storage stock has one inflow: seasonal Maize production and two outflows: Maize sales rate and post-harvest loss rate.

Maize storage stock secures sufficient food for consumption, supplements income from food sales, and enhancement of food production capacity. Food consumption is a function of food demand.

The amount of self-consumption increases to a degree with an increase in the Maize availability, which implies the number of small-scale households with adequate food to eat. The Maize demand is dependent on the amount of Maize consumed. The relationship between Maize availability and Maize for consumption is given by:

Maize_available_for_self_consumption(t) =

Maize_available_for_self_consumption(t - dt) + (Ma|ize_bought +

Monthly_Maize_consumption =

MIN(Maximum_Maize_available_for_consumption,
Monthly_food_demand_covered_with_Maize_in_small_scale_farmer_households)

The stock of Maize availability for self-consumption is increased by the inflow of Maize storage and depleted by one outflow: Maize consumption. The Maize purchase rate regulates the amount of desired Maize to purchase from the market, which depends on the food expenditure compared to the Maize market price. The availability of food in the model is a crucial element of the prevalence of nourishment. The monthly food consumption of the household population is determined by the availability of Maize. The quantity of Maize consumed is related to the amount of desired food, which depends on the household population and the food need per capita. The farmers have access to sufficient food when the desired food consumption is equal to consumption.

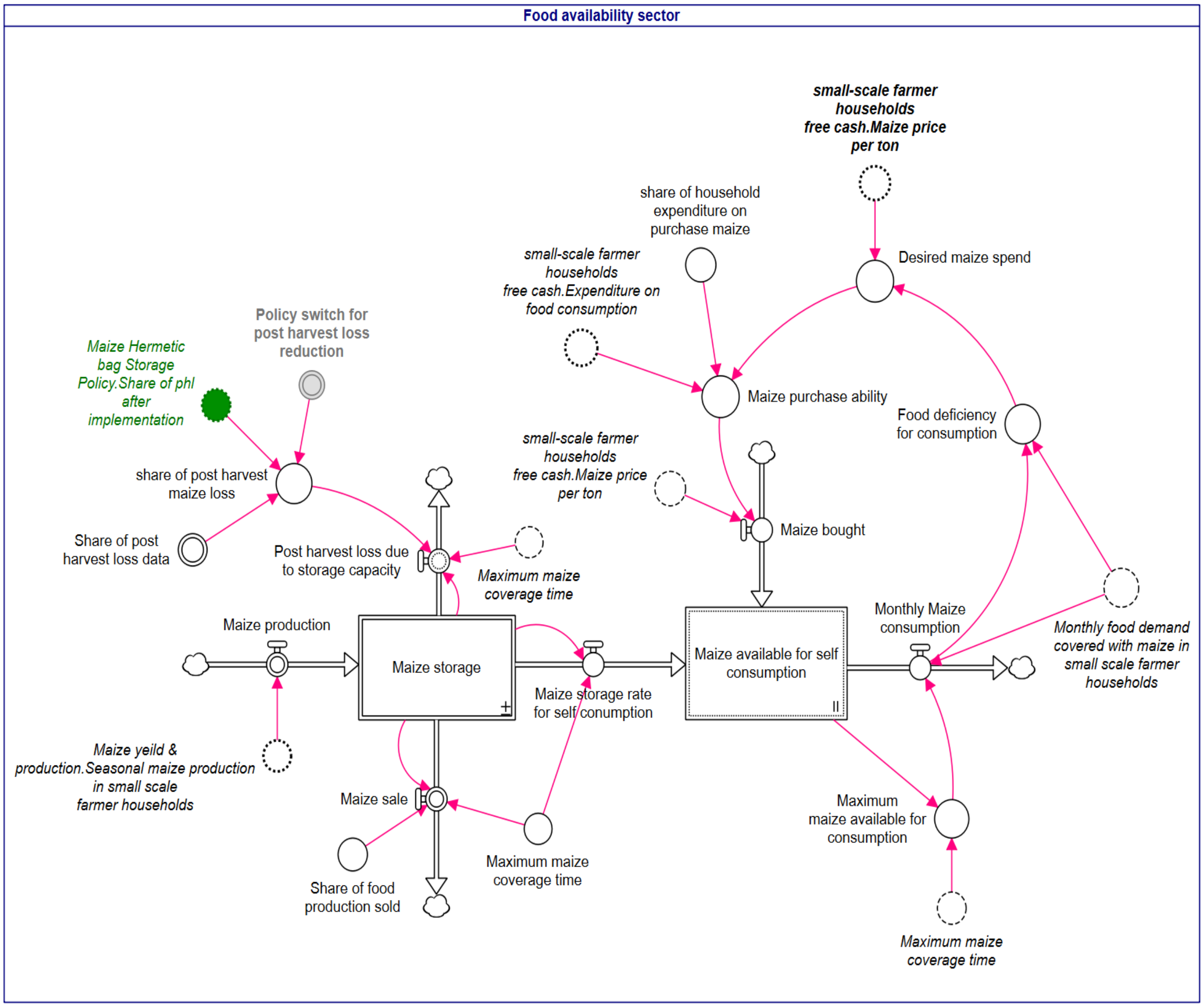


Figure 24: Stock and flow of the Maize availability sector.

4.2.1.9.2 Population growth and demand sector:

The population dynamics is crucial to assess the food consumption demand of the population. The total food consumption of the population is achieved by multiplicating the size of the population and the average per capita food consumption requirement to live a healthy life. This graph illustrates the dynamics of the population where the population stock has one inflow as “births” and one outflow as “deaths,” respectively. The size of the small-scale household populations calculated by multiplying the total population with the percentage of the household population. An increase in the overall population increases food demand.

Monthly food cdeficit is calculated by the following equation:

Monthly food deficit = (Desired kcal consumption from maize – kcal consumption from maize)*undernourished population/ small scale farmer households population.

UNITS: Kcal/Months

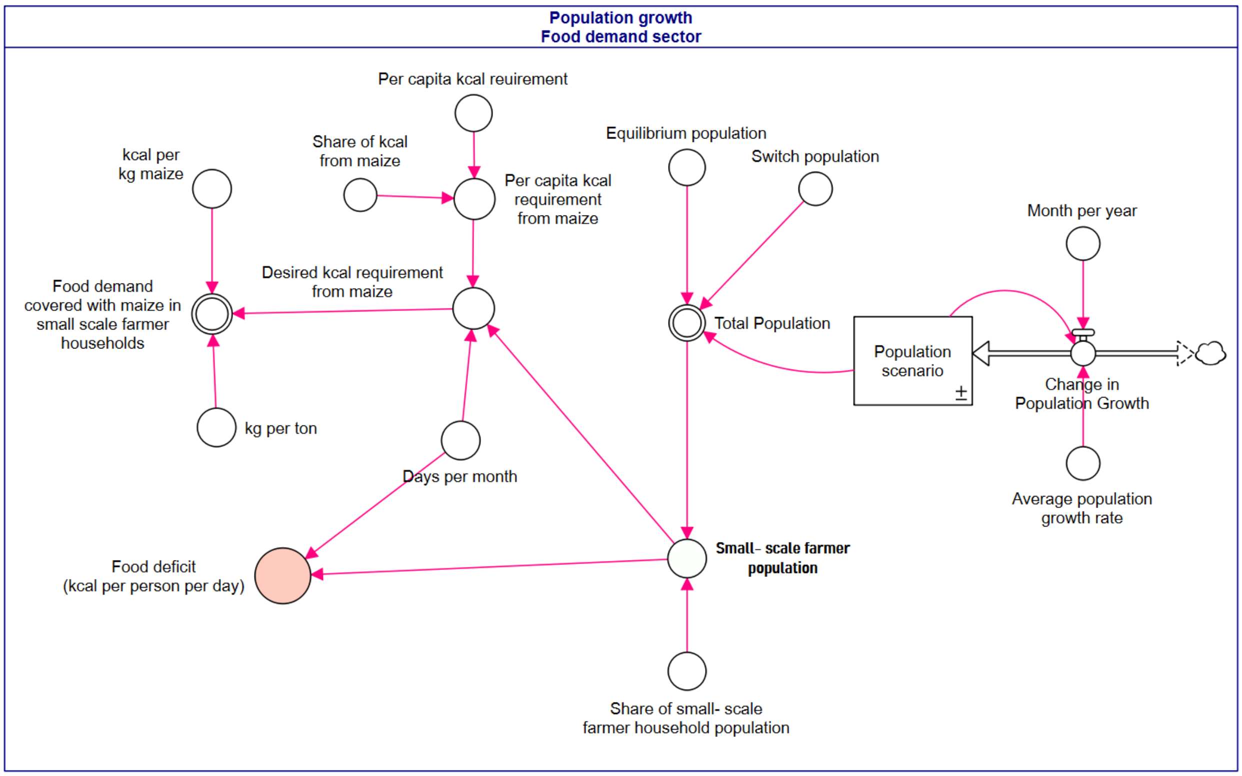


Figure 25: stock and flow structure of the population growth and food demand sector.

4.2.1.9.3 Prevalence of undernourishment sector:

The prevalence of undernourishment is an estimation of the proportion of the total population whose calorie intake is insufficient. An increase in the adequately nourished population implies an increase in available kcal per capita from Maize. The prevalence of undernourishment is calculated from the ratio of undernourished households with a total population. The equation is given below.

Population_nourished = (Monthly_kcal_consumption_from_Maize_in_small_scale_farmer_households/(Monthly_desired_kcal_from_Maize_in_small_scale_farmer_households/"Small-_scale_farmer_population"))*"Small-_scale_farmer_population"

UNITS: person

Prevalence_of_Undernourishment=

(Desired_Population__Nourished- Population_Nourished)/Desired_Population__Nourished

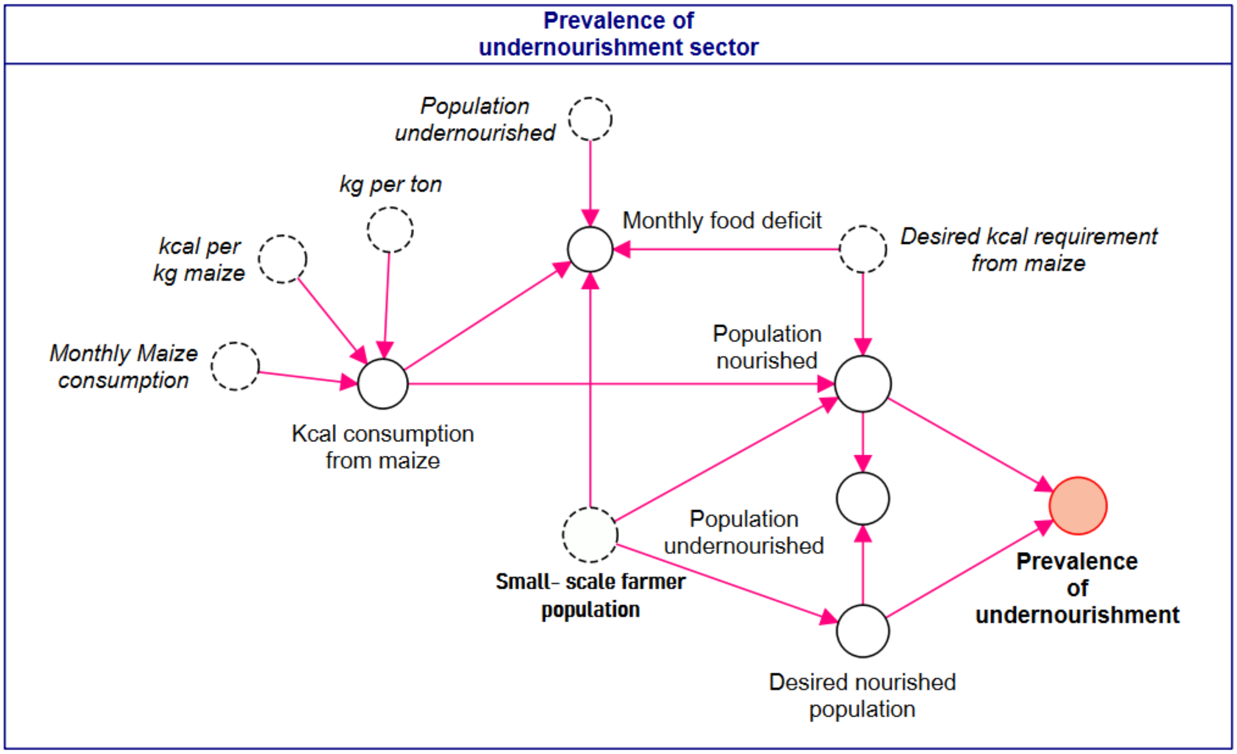


Figure 26: Stock and flow Prevalence of undernourishment sector

4.3 Feedback Analysis

This chapter describes a general overview of the model concerning its main feedback loops. Richardson & Pugh defined feedback as " a closed sequence of causes and effects, that is, a closed path of action and information" [70] Feedback occurs when a reaction affects the action itself, either amplifying (positive) or attenuating (negative) the output. There are central concepts of system dynamics and are used to illustrate the dynamic structure of systems through diagrams. Causal loop diagram (CLDs) is a simplified illustration to show the causal relationship of a system and is presented as arrows to show the direction of the effect [86]. CLD allows understanding the dynamic interrelation between loops in a system. CLDs are easy to build, but they have some limitations; they are not comprehensive and provisional. CLDs are commonly applied in academia and in the business domain to create mental models. They can also be used to show the crucial feedback responsible for a problem and raise awareness about the unintended effects of policies.

These feedback loops can either be positive (or vicious cycle) and negative (goal-seeking) loops. Positive loops happen when the change affects in the same direction as it was altered, leading to amplifying the output of the system. Conversely, in the case of negative loops, the reaction affects the action in the opposite direction leading to balance and equilibrium in the system output (B).

To illustrate the dynamics of the seasonal food insecurity in small-scale farmer household levels through the model, a causal loop diagram (CLD) was created, which is shown in the following figure.

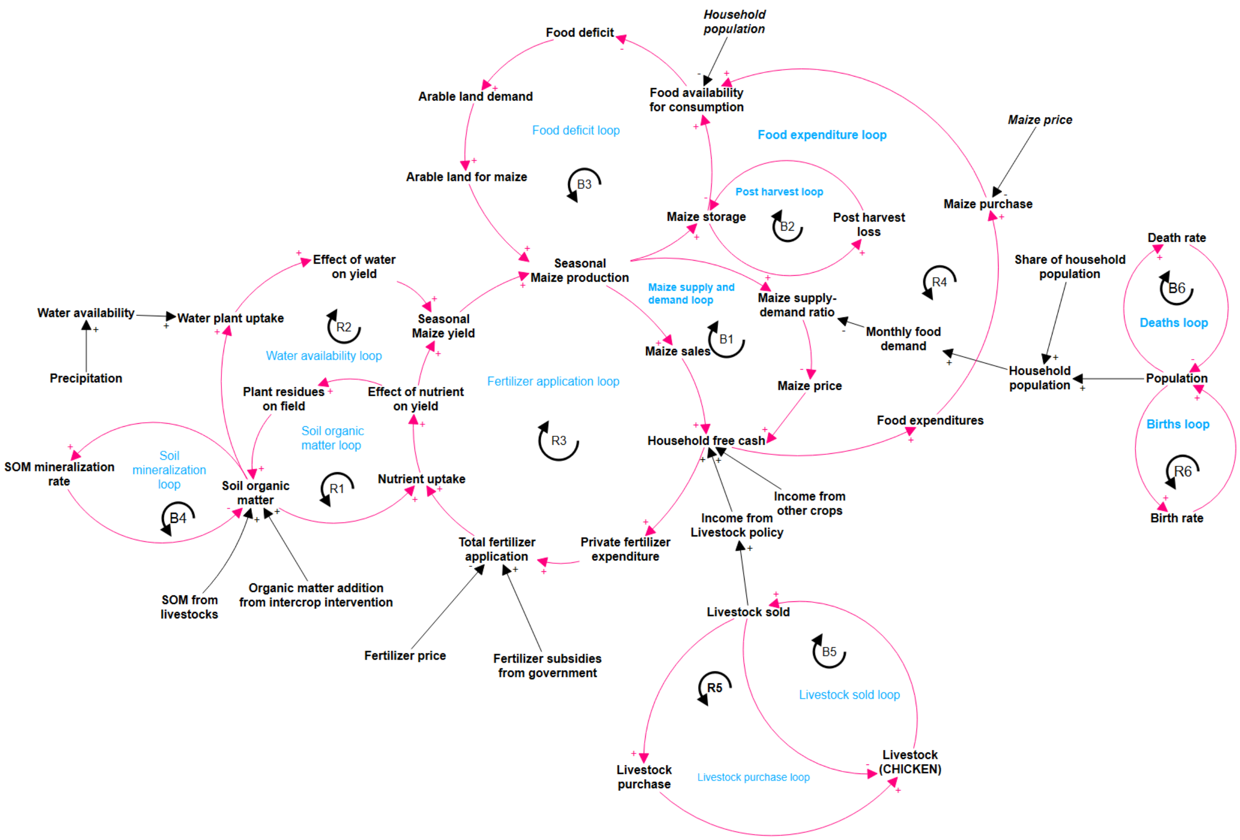


Figure 27: A causal loop diagram showing the feedback loop of the food insecurity system in Zambia

Figure 27 has five balancing feedback loops and five Reinforcing loops. All the feedbacks loops are numbered, and a short description for each loop is given below:

Soil organic nutrients reinforcing loop (R1): The "Soil Organic Nutrients Loop" (R1) signifies the positive association between plant residues left on the field after harvesting and Maize yield. Plant residues increase the biomass and soil organic nutrients that increase the Maize yield.

Water availability reinforcing loop (R2): The water availability loop (R2) represents the positive effect of total water availability on Maize yield. Availability of sufficient water in soil enhances the metabolic activity of Maize plants, escalates its biomass accumulation, and increases leaf area index (LAI), and higher photosynthetic activity, eventually resulting in better growth, development, and an increase in Maize yield [87].

Fertilizer reinforcing loop (R3): The "Fertilizer Loop" R3 shows the positive correlation between total fertilizer application and Maize yield. The price of fertilizer negatively affects the fertilizer application. It has a positive association with fertilizer expenditure, which implies that total fertilizer application decreases with an increase in the fertilizer price. Likewise, the total fertilizer application per hectare is positively associated with fertilizer subsidy and fertilizer expenditure. The higher the quantities of fertilizer applied per hectare, the more yield is achieved.

Food expenditure reinforcing loop (R4): The "Food Expenditure Loop" (R4) illustrates food expenditure positively affecting total food availability. Households earn free cash from selling Maize and other crops. If the household has a higher amount of free cash, the expenditure for food goes up. Besides this, the amount of purchased Maize is inversely related to Maize prices. With an increase in the Maize purchase, the availability of food for consumption becomes higher.

Food deficit balancing loop (B1): The food deficit loop represents a negative effect that the food deficit has on food availability on consumption. Lower food deficit is caused by an increase in the production of Maize, which makes the more food available to farmers, which means there is no need to use additional agricultural land for growing Maize, as Maize area is proportional to the agricultural land. Therefore, lower agricultural land used will lead to less Maize area, which affects less Maize production next time around.

Maize demand and supply balancing loop (B2): The Maize supply and demand loop (B2) demonstrates the negative effect on each other while maintaining the supply-demand ratio. When the supply and demand increase simultaneously, the ratio remains the same, and there is less Maize deficit among small-scale farmers. Consequently, an increase in Maize production leads to lower Maize prices, which eventually could lower the income of the farmers. In the absence of government subsidies, the farmers cannot afford to buy fertilizers in the next season that again lead to poor Maize yield. This less Maize production affects the supply-demand ratio and leading to an increase in the Maize price. The food availability is compromised in the small-scale farmer households, as they cannot purchase food at a high price.

Post-harvest loss balancing loop (B3): The post-harvest loss loop depicts the harmful effect of how the post-harvest loss decreases Maize storage. The amount of post-harvest loss is inversely proportional to Maize storage, affecting food availability and food insecurity. On the contrary, less post-harvest loss supports increase Maize storage, which results in lower food-deficit through the lean season of the year.

Birth loop (R5) & Death loop (B5): Finally, the “Births Loop” (R5) and “Deaths Loop” (B5) show the factors that affect the size of the population. The household population grows over time, which implies an increase in food demand in the future. Therefore, to evaluate the intermediate and long-term effects properly, it is essential to consider these determinants, estimate of food demand, and formulate policies accordingly.

4.4 Model Boundary and Basic settings

Despite that CLDs represent the useful causal relationship between the variables, they are not suitable to simulate the long term behavior of a system due to the inherent focus on the qualitative and conceptual insights of the system. Conversely, stock and flow diagrams emphasize the quantitative aspect of a system dynamics model [64]. A system can be represented as an aggregation of stocks and flows or rates; thus any information that is accumulated in stocks and changes at a rate (flows) between them [88]. We created a quantitative and integrative dynamic model to look in-depth into the dynamics of seasonal food insecurity among small-scale farmers in Zambia. To evaluate the long-term behavior of the seasonal Maize production and effects of the policies, we used monthly time steps up to 360 months (30 years). The simulation model is rectified with Stella Architect, a dynamic visual simulation-based modeling software (isee systems, NH, USA). The model is fully standardized as per the guidelines of Rahmandad & Sterman, which is included in the Appendix, and the Stella “.stmx” model file is attached to this thesis [89].

5 Model validation

Model validation is an essential aspect of model-based analysis. It serves as the foundation upon which a model can generate the appropriate behavior following changes, and creating a framework for further methodology processes. Validity ensures that the model is suitable to serve the specific purposes for which it was created. In system dynamics modeling, the model is scrutinized by various tests to build confidence in its usefulness, which is referred to as the validation of the model [70]. There is no established method to perform proper validation of a model. At the same time, there is no standardized guideline to consider a model as validated. [64, 67]

The system dynamic approach is iterative and simplified representations of reality. However, despite iteration, it is not possible to validate a model thoroughly due to the complexity of the problem. Therefore, all models always have the scope of improvement somehow[64]

The validity in system dynamics refers to the model's robustness rather than the output behavior [90]. Validity does not imply just only the replication of the behavior because the model can behave expectedly but for the wrong purpose. Instead, models should serve the specific purpose while testing the validity, and the validation process should be focused on achieving the goal of the model.

The validity of the current model is tested in three stages: direct structural tests, structure-oriented tests, and behavior pattern tests following the guidelines suggested by Barlas [67]. Moreover, the methods for conducting the validity tests are described in detail in each section. This chapter provides an overview of it and illustrates the system under study while establishing confidence that the model justly represents the system.

5.1 Direct Structure test

A structure assessment test is performed to evaluate how well is the model structure represents the real-world scenario [64]. This is done by taking each relationship through a mathematical equation and comparing it with detailed knowledge about the system [67]. Endogenously variables are crucial while doing structural assessment tests because they indeed regulate the behavior of the system. Therefore, it helps determine the flaws in the model structure in contrast to the real systems and to resolve them accordingly.

In chapter four, both the causal-loop and stock-flow model structure was presented, in which the systemic interaction between various parameters creating problematic behavior is described. The model structure illustrates the causal hypothesis describing the interaction between various determinants over time. Therefore, the validity of the model is subjected to the validity of the model structure. The conceptualization and definition of the model structure are based solely on the knowledge portrayed in the research literature. To develop the model structure, several documents, research results, and surveys have been used. The works of Gerber was used as the groundwork to build the main structure of Maize yield and soil dynamics structure [38]. In addition, data from different time-series surveys from CSO, IFRI, World Bank, FAO, were also used. To test model sensitivity to several of the estimated parameter values, a sensitivity analysis was performed in section 5.6.

5.2 Dimensional consistency test

Dimensional consistency test is a fundamental method for model validation, which is used to check the consistency of the units in the model. Here, all the equations and units of measurements were put together without using parameters and variables to test the consistency, ensuring that the model is compatible, robust, and precisely representing the intended variable [64]. All the variables in the model reflect the real-world dynamics of the food insecurity system and are connected and influenced by other variables. The unit consistency was tested by Stella Architect simulation software by going through the following steps-

i. In the Model mode, all the equations in the model are entered. If there is any unit inconsistency, the run toolbar shows the number of inconsistent variables. This function is unavailable in the Map mode.

ii. The Run toolbar displays no error message if all the units are consistent.

iii. There is a drop-down list by the side that displays the inconsistent variable.

iv. Using the Check Units key in the menu next to the units, we can get additional information on the inconsistency type.

Following all these steps suggested by the isee system, the software shows that all the units are consistent, which is apparent in the following figure after using the Run toolbar. No error message was displayed. Thus, it confirms that the model is dimensionally consistent.

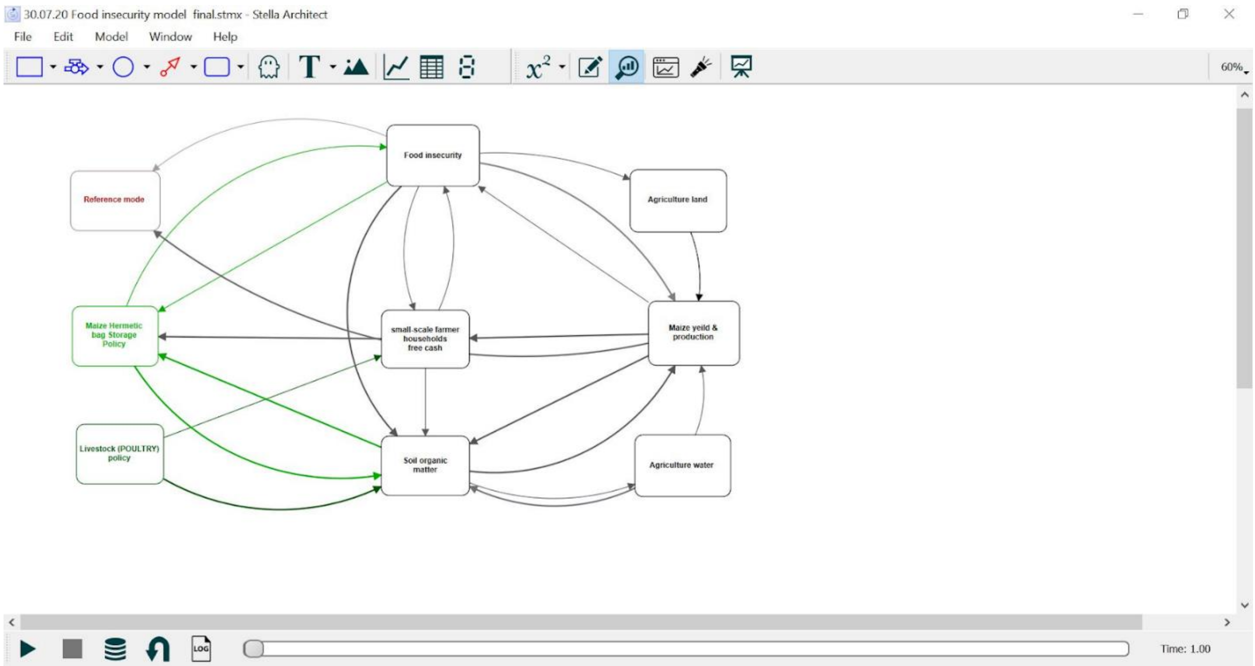


Fig 28: Dimensional consistency test in Stella software

5.3 Boundary Adequacy Test

Boundary adequacy test is performed to elucidate whether the elements are endogenized, and changes in the boundary affect the behavior of the model, change policy recommendations. The boundary adequacy test corroborates the model's purpose to the structure and validates if the research questions are answered. This model aims to identify the responsible factors for food insecurity at the household level and delineate policies to improve the food security system.

In this study, Maize production is the primary variable driving the Maize storage, household free cash, agriculture land demand, Maize purchase ability, expenditure on fertilizer use, Maize availability for consumption to calculate the prevalence of undernourishment and food deficit. Maize production and yield depend on the availability of SOM in the soil and the use of fertilizers. Moreover, we looked into the dynamics of the land sector that is used for Maize production. Maize deficiency is the prime factor that determines land demand. Therefore, to evaluate the Maize availability, the Maize storage sector was considered. These key endogenous factors in the model are essential to consider understanding the complex dynamic system. Several interactions are portrayed in the model endogenously, such as the interaction between SOM availability and Maize production, the interaction between supply demand balance and agriculture land.

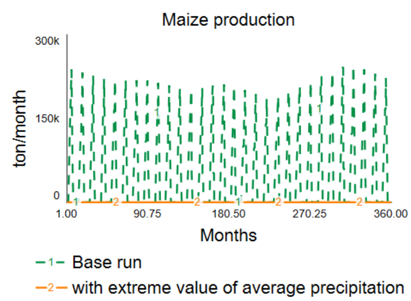
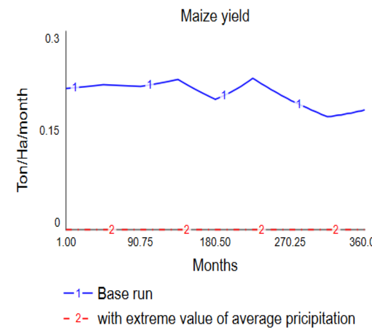
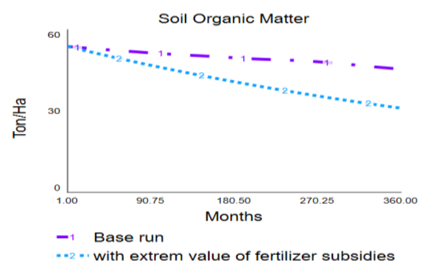
Although relevant, the population dynamics and the production and yield of other crops were excluded and considered exogenous in the model due to time constraints. The focus is on the production and availability of the staple food for consumption to ensure food security at the household level based on the prevalence of undernourishment and food deficit indicators..

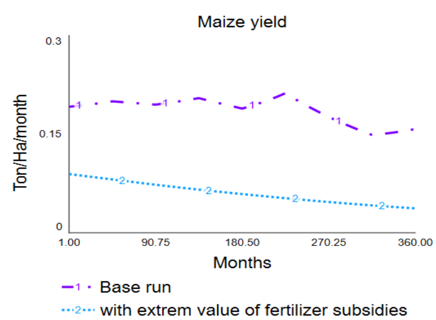
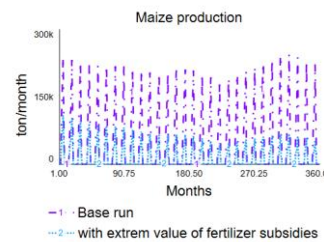
In light of this, the model has six modules; food security, agriculture land, Maize yield & production, household free cash, Soil organic matter (SOM), and agriculture water availability. This will allow us to include as much as possible the feedback process among Maize storage/ food available for consumption, sale of Maize and household free cash and expenditure, SOM, and Maize yield to determine the holistic interaction among these variables. Thus, a framework is developed for informed policy options that encourage the development of the food insecurity process. The model structure reflects that the model passes the boundary adequacy test, presented in chapter four and the appendix.

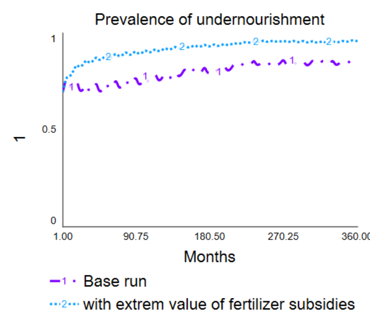
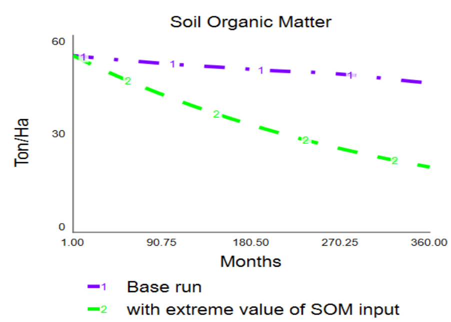
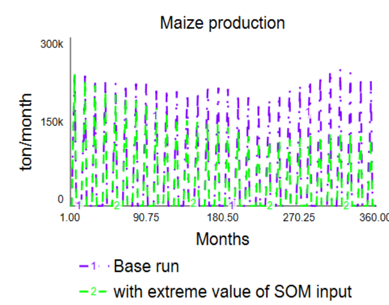
5.4 Extreme conditions validation

In system dynamics, the validity of the model is tested by putting extreme policies, shocks, and parameter values into it. The model is considered robust and consistent if it shows realistic results under extreme values, which is unlikely to happen in real life [91]. The equations are put in extreme values. The resulting values were checked for plausibility, whether the output is in line with the expected behavior under similar conditions in real life [67]. While testing, the stocks are regulated and not allowed to go to zero or reach negative values because even in extreme cases, stocks in real-world systems do not attain negative values. Any division by zero results in a floating error. The following table shows the behavior of the model in some extreme conditions. The outcomes are discussed below in the table.

Table 4: Extreme condition tests

<table>
<tr><th>Extreme Parameter value</th><th colspan="2">Simulated behavior</th></tr>
<tr><td>Average precipitation=0</td><td>
</td><td>
</td></tr>
<tr><td>Fertilizer subsidies=0</td><td>


</td><td>


</td></tr>
<tr><td>SOM input=0</td><td>
</td><td>
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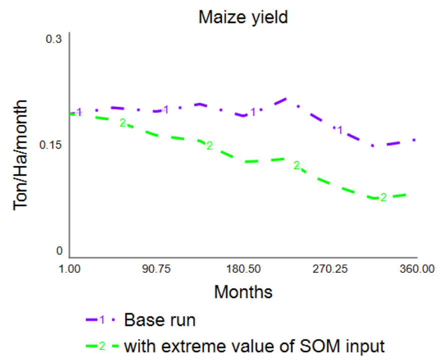
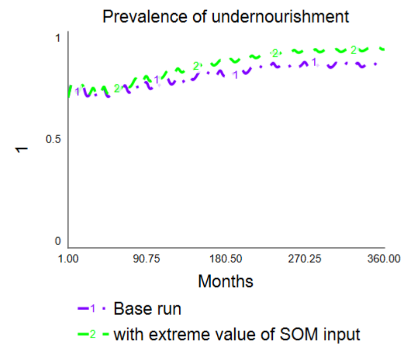
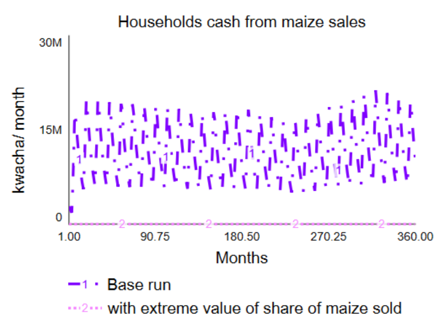
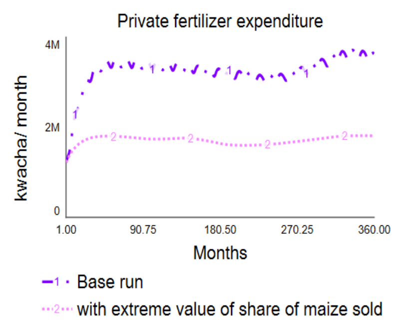
		
Share of Maize sold=0		

Table 4: validation of the model in extreme condition

From the extreme condition tests, it is evident that all the rate equations are valid, which indicates the model behavior in a more real-world perspective. We know that the extreme changes in parameter values should give the logical direction in the behavior in the model variables. For instance, the behavior of several vital elements of the system was tested – soil organic matter, Maize yield, Maize production, Maize storage, household income and prevalence of undernourishment. Some unexpected values were put in the average precipitation, fertilizer subsidies, and SOM input rate, the share of Maize sold. In the extreme condition of no fertilizer subsidies (fertilizer subsidies = 0), the Maize yield and production declined due to decreased SOM that leads to higher prevalence of undernourishment among small scale farmers.

When the average precipitation equals 0 mm/month (extreme drought), the yield and production of Maize are expected to go to zero. The simulation results are shown in the above figure, indicating severe drought (average precipitation= 0), the Maize production and yield was zero. Similarly, when the SOM input rate is zero, the soil organic matter must be decreasing, so the Maize production should also decrease, and the prevalence of undernourishment increased than the base run. Finally, the model is considered as robust from the extreme condition test and the rate of the equations is meant to be justified for further study.

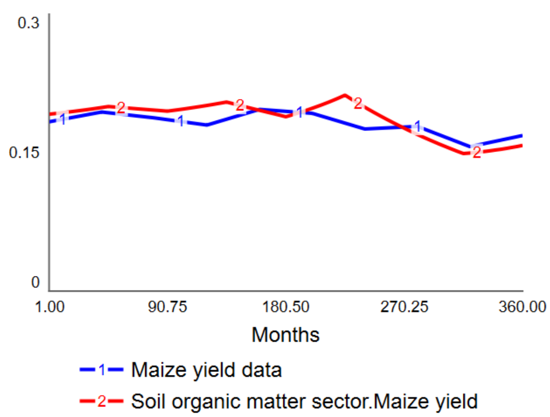
5.5 Structure- behavior test

Structure-oriented behavior test is performed to assess whether the behavior of the model matches the desired behavior, both qualitatively and quantitatively in regards to the purpose of the given system. It also allows us to determine whether the modes of behavior and modeled relationships among variables in the model go in line with the observed behavior in the real system [64]. In contrast to the direct structure test, it evaluates the structure's validity indirectly by checking the model generated behavior patterns and points on a specific behavior [67].

5.5.1 Pattern and point check

During validation, the simulated model behavior is compared with past behavior to evaluate whether it accurately represents the system's behavior. In this study, reference graph were drawn to capture the historical output (behavior) of key variables of Maize yield, Maize production and Maize harvest area that assess the food incurity.

The model was run for 360 months(from 2010 to 2040), where the external inputs for the first eight years (108 months) were factual data, and the rest was based on realistic assumptions about the future behavior of the input.



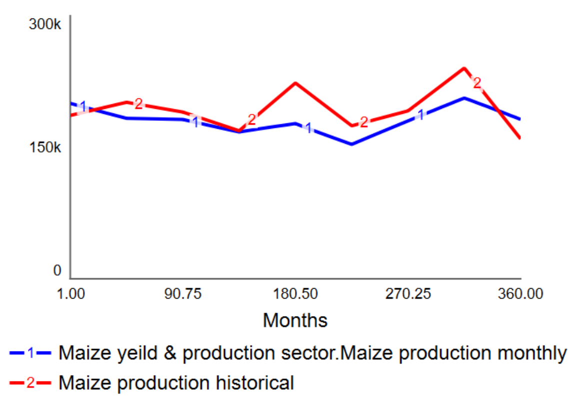


Figure 29: Comparison between historical behavior and simulation behavior Maize yield and Maize production.

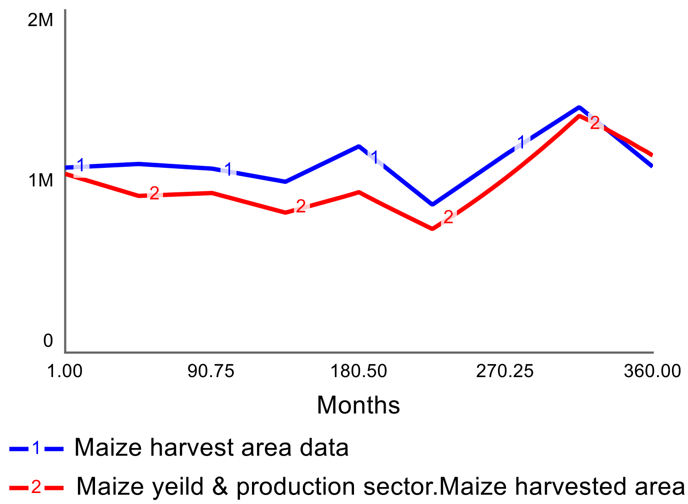


Figure 30: Comparison between historical and simulation behavior of Maize harvest area .

Figure 29 and figure 30 shows that the reference mode's behavior is very similar to the simulated behavior of the Maize yield, Maize production and Maize harvested area. Hence, it indicates that the model has a solid ground for policy design and can provide a feasible solution to the problem.

5.6 Sensitivity Analysis

The sensitivity analysis proves model's sensitivity and responsiveness in the behavior mode in response to changes in parameter values and leads to change in the policy implications. Usually, sensitivity analysis is dependent on estimated data based on statistics or previous studies. Besides testing the sensitivity, it also allows us to understand why the real system would show similar sensitivity to the parameter changes in the same direction [90]

In this model, the sensitivity analysis was performed by changing the parameter value of 50 % below or above the base case run value to observe the simulated behavior. Moreover, The value was doubled, i.e., increased by 100% in some parameters, which implies the confidence interval between two simulation behaviors is fifty percent. The changes in exogenous variables are often overlooked to keep the model's boundary limited and focused as much as possible.

In this study, sensitivity tests have been conducted for the selected variables that are given below:

Sensitivity Variables	Base run value	Values for sensitivity analysis Minimum (50% below)	Maximum (50% above)	Doubling (100 % above)	Tested variables
Maize harvest area for small scale farmers	13700000	6850000	20550000	27400000	Maize production Prevalence of undernourishment Food deficit
Fertilizer subsidies	1800	900	2700	3600	SOM Maize yield Prevalence of undernourishment Food deficit
Share of remaining plant residues in the field	0.5	0.25	0.75	1	SOM Maize yield Prevalence of undernourishment Food deficit
Share of plant residues in produced biomass	0.5	0.25	0.75	1	SOM Maize yield Food deficit Prevalence of undernourishment
Average precipitation	1200	600	1800	2400	Maize yield Maize production Food deficit Prevalence of undernourishment

The average Population growth rate	0.0286	0.0143	0.0429	0.0572	Desired kcal requirement from Maize Prevalence of Undernourishment Food deficit
SOM mineralization time	360	180	540	720	SOM Maize production Food deficit Prevalence of undernourishment
Share of post-harvest loss	0.45	0.225	0.675	0.9	Maize storage Prevalence of undernourishment

Table 5: Values for sensitivity analysis

5.6.1 Maize harvested area in small scale farmer households

Maize harvest area has a causal relationship with the Maize production, Maize yield, and prevalence of undernourishment (PoU). Hence it is a crucial variable in this model. A higher Maize harvest area leads to increased Maize production and yield, resulting in a lower prevalence of undernourishment (PoU). On the other hand, the lower Maize harvest area causes the opposite effect on the other four variables.

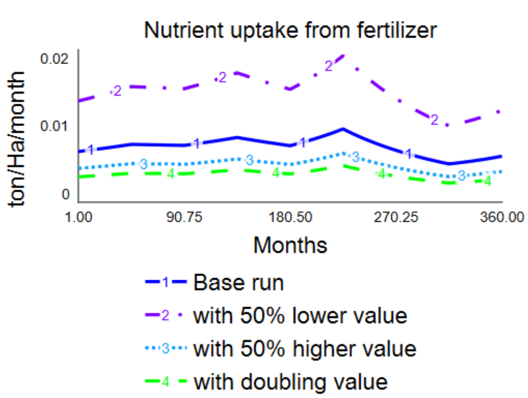


Figure 31 (a) : Nutrient uptake from fertilizer

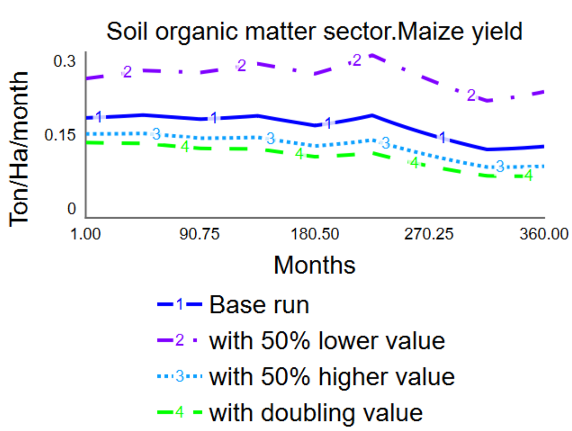
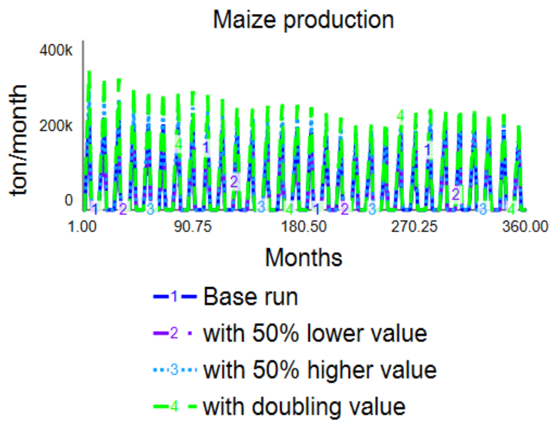


Figure 31(b): Maize yield



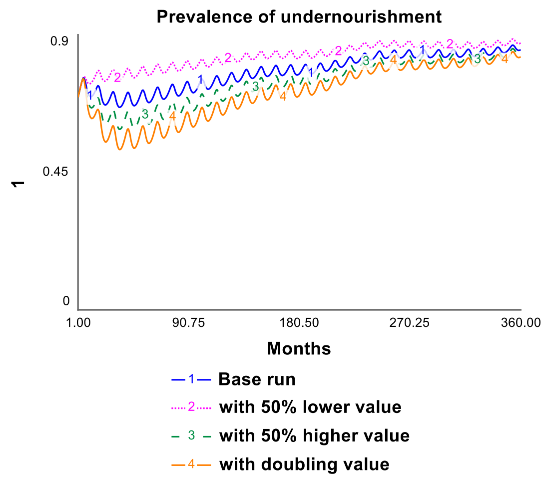


Figure31 (c): Maize production *Figure 31(d): Prevalence of undernourishment (PoU)*

Figure 31: The sensitivity analysis of maize yield and production, nutrients uptake from fertilizer and prevalence of undernourishment with the Maize harvest area for small scale farmers.

Figure 31(a-d) shows the sensitivity analysis of nutrients uptake from fertilizer, Maize yield, Maize production, and prevalence of undernourishment (PoU) with the change in the Maize harvest area. Nutrients from fertilizer and Maize yield in Figure 31 (a) and 31 (b). These two variables are more sensitive to the Maize harvest area changes for small scale farmers than the other variables such as Maize production and PoU. When the Maize is harvested in less area, it results in higher nutrients from fertilizer and higher Maize yield than larger Maize harvest areas. However, higher Maize production harvest area leads to higher Maize production that eventually decreases PoU.

5.6.2 Fertilizer subsidies

Fertilizer subsidies parameter is another vital parameter in the system as it facilitates the availability of nutrients for the Maize plants.

Figure 32 (a-d) shows the sensitivity analysis tests of the model's behavior following a change in fertilizer subsidies. Hence, it results in lower SOM that further leads to low Maize yield as the farmers depend on the subsidies to buy fertilizers. The more the subsidies are, the more fertilizer can be bought that leads to improved Maize production, which could decrease the food deficit and PoU.

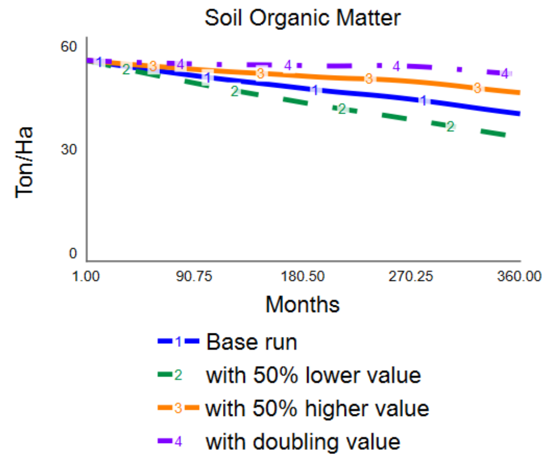


Figure 32(a): Soil organic matter

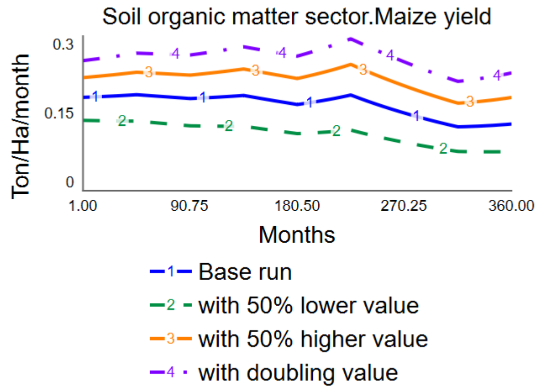


Figure 32(b): Maize yield

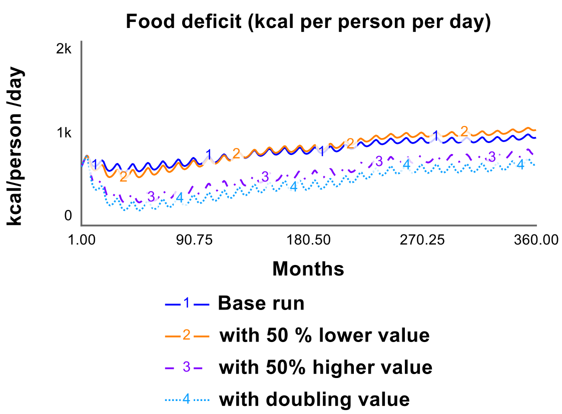


Figure 32(c): Food deficit

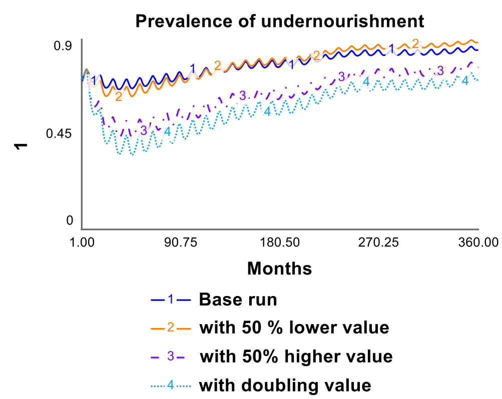


Figure 32(d): Prevalence of undernourishment

Figure 32: The sensitivity analysis with fertilizer subsidies.

5.6.3 Share of remaining plant residues in the field

The following graphs 33 (a-d) show that Maize production and soil organic matter are sensitive to the change in the value of plant residues in the field. If the farmers left more remaining residues, which is converted into soil nutrients, that could boost the Maize yield. Thus, plant residues in the field affect the food deficit and PoU among small scale farmers in Zambia.

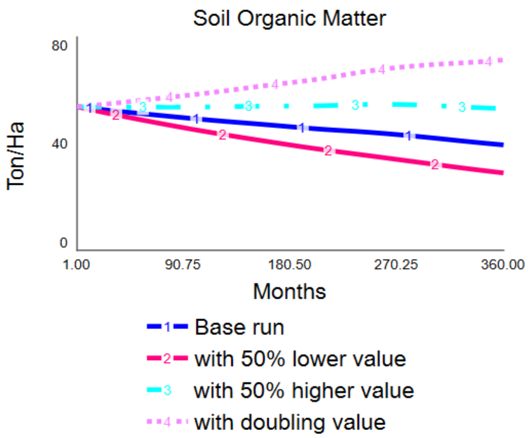


Figure 33 (a): Soil organic matter

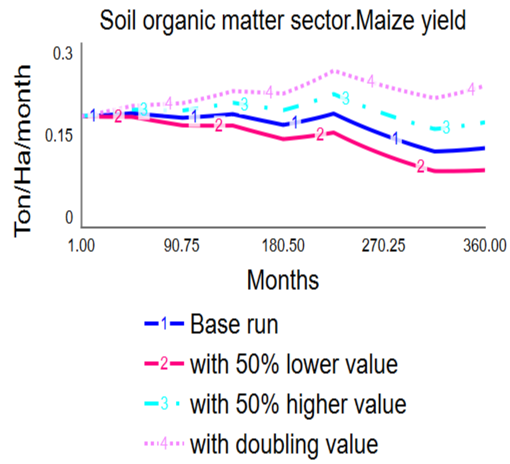


Figure 33(b): Maize yield

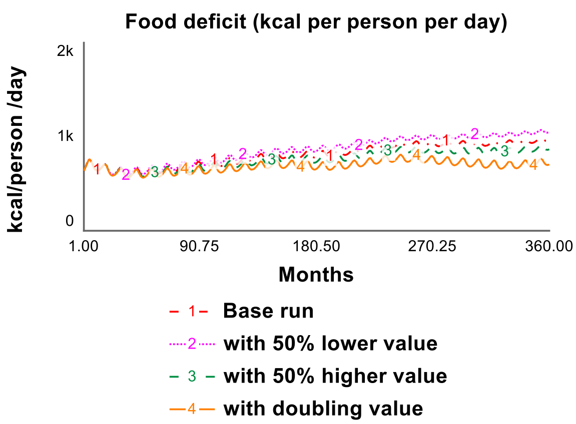


Figure 33(c): Food deficit

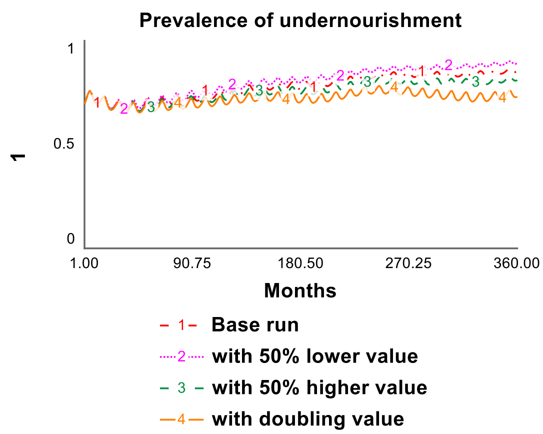


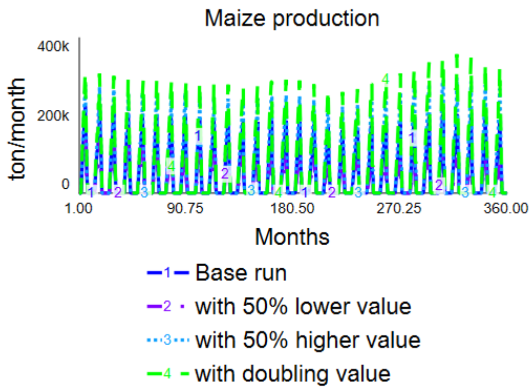
Figure 33(d): Prevalence of undernourishment

Figure 33: The sensitivity analysis with the share of plant residues in the field.

5.6.4 Average annual precipitation

Average precipitation determines the availability of water, making it one of the most sensitive parameters in an agricultural system—a decrease in the annual average precipitation results in decline in the Maize yield and Maize production. As most of the Zambian farmers do not have irrigation facilities, rainfall is the primary way of water supply, making it crucial for Maize cultivation in Zambia.

Figure 34 (a-d) shows the sensitivity of Maize yield and Maize production, which affects food deficit and PoU with a change in annual average precipitation.



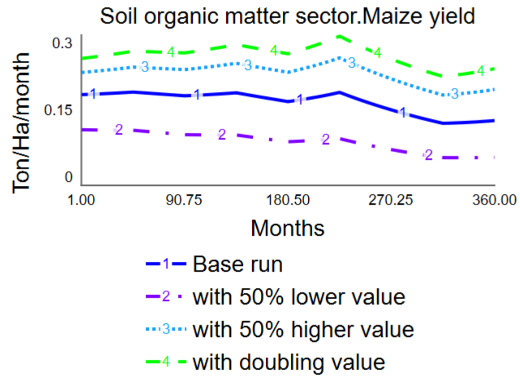
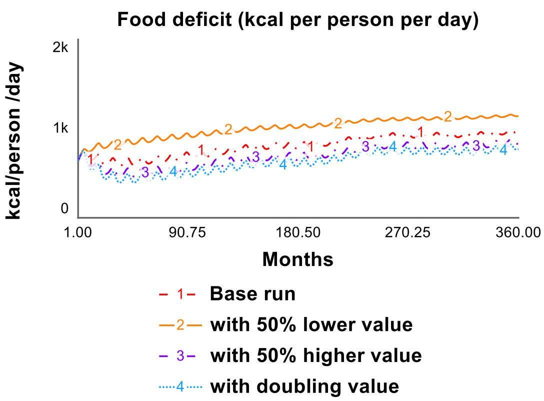


Figure 34 (a): Maize yield *Figure 34(b): Maize production*



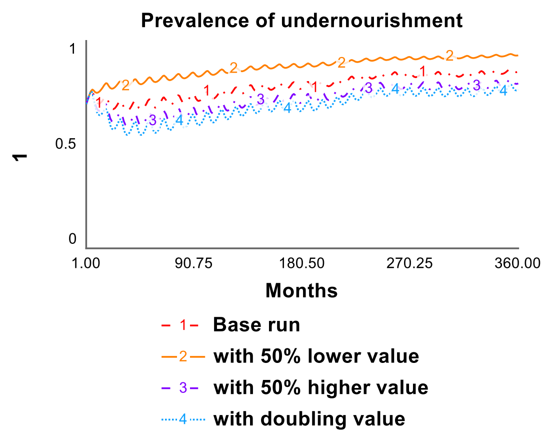


Figure 34(c): Food deficit *Figure 34(d): Prevalence of undernourishment*

Figure 34: The sensitivity analysis with the annual average precipitation

5.6.5 SOM mineralization time

The mineralization of soil organic matter from the stock of SOM is a slow process. However, a change in the mineralization time is sensitive to the stock of soil organic matter and Maize yield. If the mineralization time is quicker, SOM depletes faster from the soil and vice versa. The amount of nutrients uptake by the soil from the SOM pool affects Maize production and Maize yield. Figure 35 (a-d) shows the sensitivity analysis test of SOM, Maize yield, food deficit, and PoU with the change of SOM mineralization time.

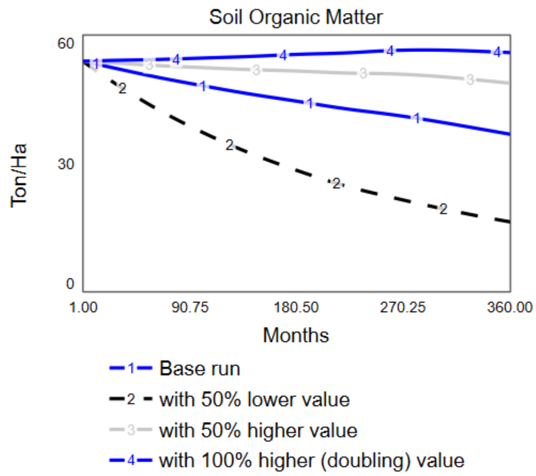


Figure 35 (a): Soil organic matter

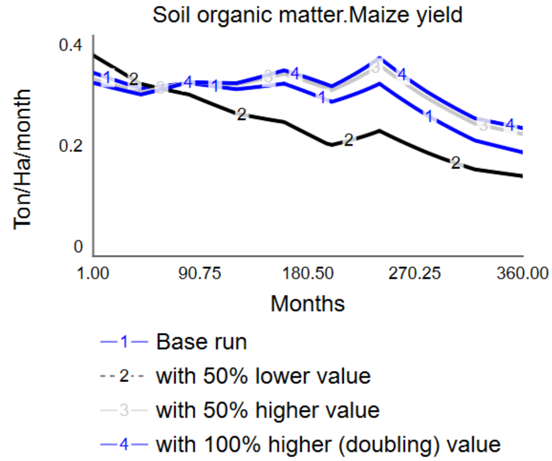


Figure 35(b): Maize yield

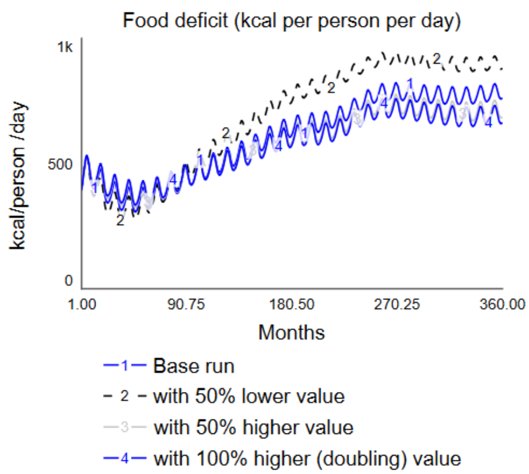


Figure 35(c): Food deficit

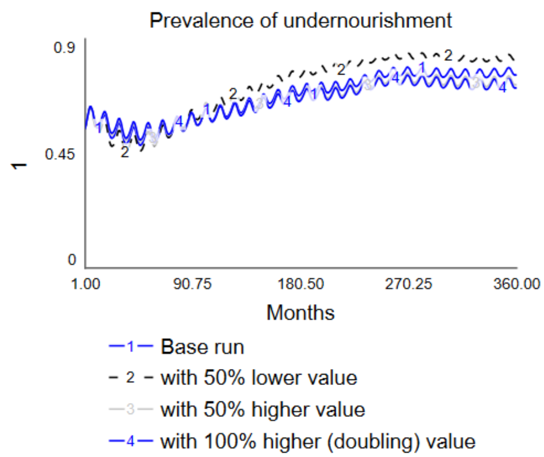


Figure 35(d): Prevalence of undernourishment

Figure 35: The sensitivity analysis with SOM mineralization time.

5.6.6 Average Population growth rate

The population is the impelling cause for the whole system that the model is designed for. The population size is sensitive to the whole system of the food insecurity model, shown in figure 36 (a-b) as higher population growth increases desired kcal requirements and decreases available Maize per capita, making it more sensitive to food insecurity. At the same time, high Maize demand causes higher consumption leading to the food deficit, creating positive feedback to increase undernourishment among small-scale farmers.

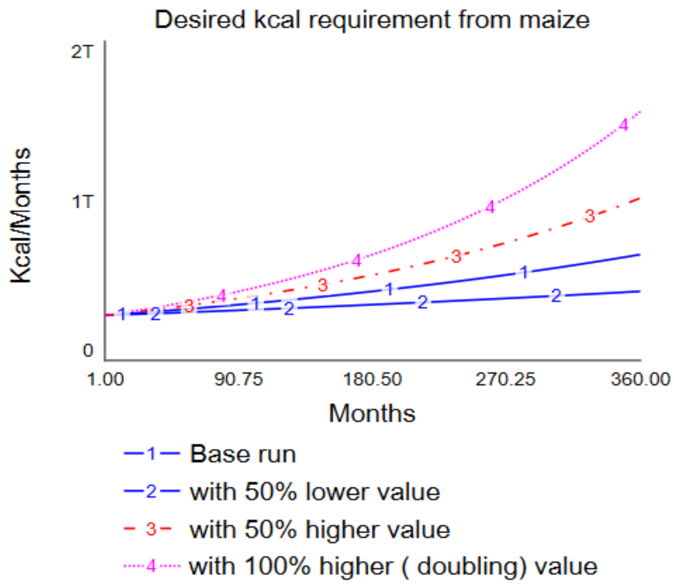
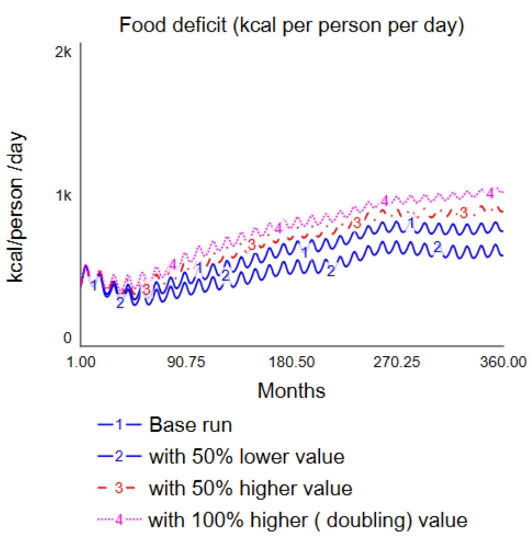


Figure 36 (a): Desired kcal requirement from Maize.



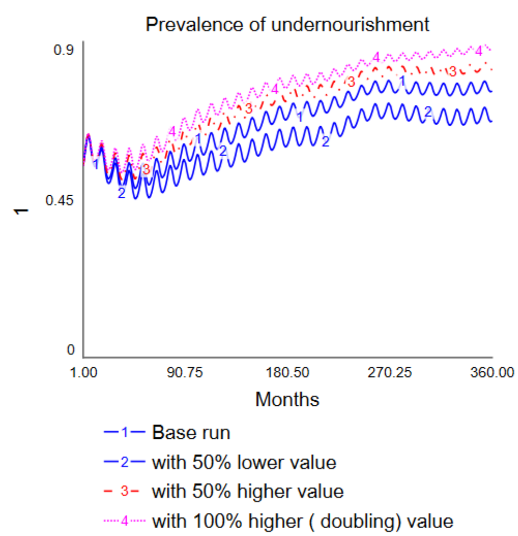


Figure 36 (b): Food deficit *Figure 36 (c): Prevalence of undernourishment*

Figure 36: The sensitivity analysis with the average population growth rate.

5.6.7 Share of post-harvest loss

Share of post-harvest loss parameters has a significant impact on the food insecurity level among small scale farmer households. Post-harvest loss reduction will increase Maize storage without increasing land, water, and agricultural inputs. The benefits to farmers from reducing post-harvest losses help to lower Maize prices and improve food security. Figure 37 (a-c) shows the sensitivity of Maize storage and its effects on food deficit and PoU with a change in the value of the share of post-harvest loss.

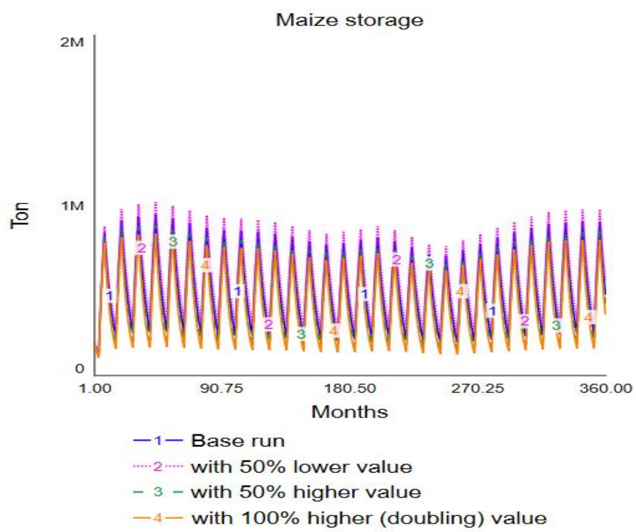
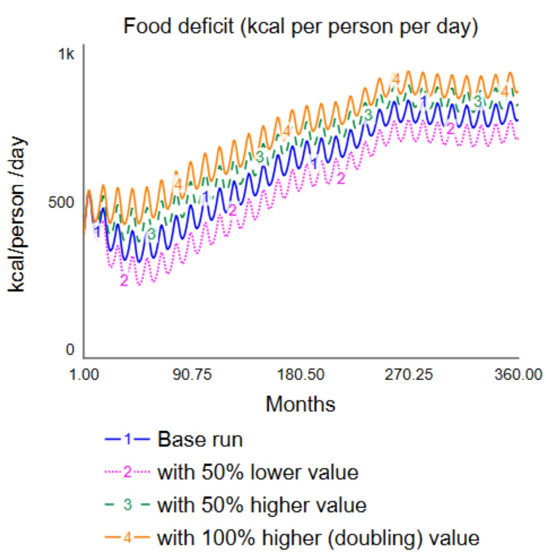


Fig. 37 (a): Maize storage



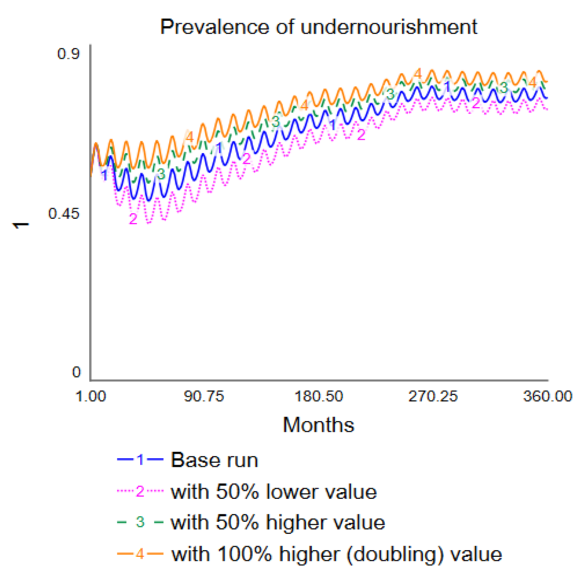


Figure 37 (b): Food deficit *Figure 37 (c): Prevalence of undernourishment*

Figure 37: The sensitivity analysis with the share of post-harvest loss.

The discussion of sensitivity analysis confirms that most of the parameters are less sensitive for the general model behavior, implying the robustness of the model. The following parameters are more sensitive to the model behavior that could be considered for further research and used for designing the policies.

- Fertilizer subsidies
- Share of plant residues remaining on the field
- Annual average precipitation
- Share of post-harvest loss

Among the parameters reduction of post-harvest loss shows the most significant changes in the system, indicating it as the most sensitive leverage point to design the policy. Besides, the government's fertilizer subsidies play a vital role in the system feasible for effective policy. Similarly, changes in the percentage of plant residues could be another dimension for policy formulation. Finally, the annual average precipitation is a crucial parameter that can improve the Maize production in Zambia if it can be improved through effective policy.

6 Behavior and Policy analysis

6.1 Behavior Analysis

This section describes the simulation behavior of the main variables with an explanation of the specific situations involved in the food insecurity system among small-scale farmer households in Zambia. The simulations display the role of main variables on maize production, which is the main factor for the availability of maize. Similarly, it is also described how different variables play household food security. The simulations were run for 30 years or 360 months (from the year 2010 to 2040), which is considered enough to analyze the household food security situation in Zambia. In each figure, the unit of time is each month, which started in January 2010; which is month 1 and February 2010 as the month 2 and so on upto month 360 which is the December 2040.

6.1.1 Behavioral analysis of Arable land and maize harvest area

The first variable that is going to be discussed is the area for maize harvest, which has crucial for maize production, as output is a function of yield and land area cultivated. Fig x (a-b) shows the simulation behavior of arable land, historical maize harvested area, maize harvest area for small scale farmers and maize production for a simulation for 30 years. The simulation shows the maize harvest area increased over time with some fluctuation while arable land and the demand for it grow, respectively. The small-scale farmers utilize a large part of the total maize harvested area, and they contribute to produce 80% of total maize production. The ever-growing population causes an increase in the food demand that leads to an increase in the demand for arable land. The simulation predicts that more land will be used to meet the demand for household food, which will reach 4,17M ha in 2040. Figure 38(b) shows the chaotic oscillations behavior of simulated maize production over time because of strong seasonal maize harvest.

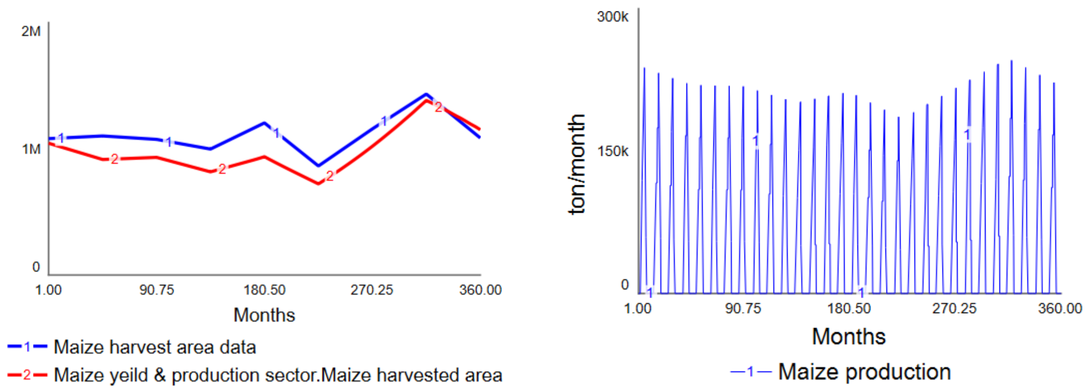


Figure 38 (a): Comparison among arable land,maize harvest area and maize harvest area for small scale farmers. Figure 38(b): Maize production

Figure 38 (a-b): Simulated arable land, maize harvest area, maize harvest are for small scale farmer and maize production.

6.1.2 Behavioral analysis of SOM and total nutrients uptake

Soil fertility is one of the most critical factors that affect maize yield. Soil organic matter retains the water from precipitation, making it available for the plants to be uptaken [92]. The amount of SOM is determined by the amount of plant residues left on the field, implying that higher yields lead to more biomass and more significantly high SOM.

Figure 39 (a-c) shows the simulation behavior of SOM, its input and mineralization rate, nutrients uptake from fertilizer, and total nutrients uptake by maize throughout the period. Total nutrients uptake is determined by the amounts of nutrients from SOM and fertilizers. With this, the SOM mineralization process controls the level of nutrients from SOM.

Figure 39(b) shows that the amount of total nutrient uptake fluctuates mildly till 190 months, followed by a sharp increase around 260 months, and then it declines sharply at the end. The simulation behavior of nutrients from fertilizer followed the same pattern as the total nutrients uptake by maize. Most smallholders cannot afford fertilizer, which is indicated in the simulation as a highly -sensitive parameter for maize production. Therefore, the government should invest heavily in fertilizer subsidies through the Fertilizer Support Program (FSP) [59]. In the model simulation, the value of average fertilizer subsidies was the same, making the behavior of nutrients follow the behavior of the maize harvest area, as shown in the previous section.

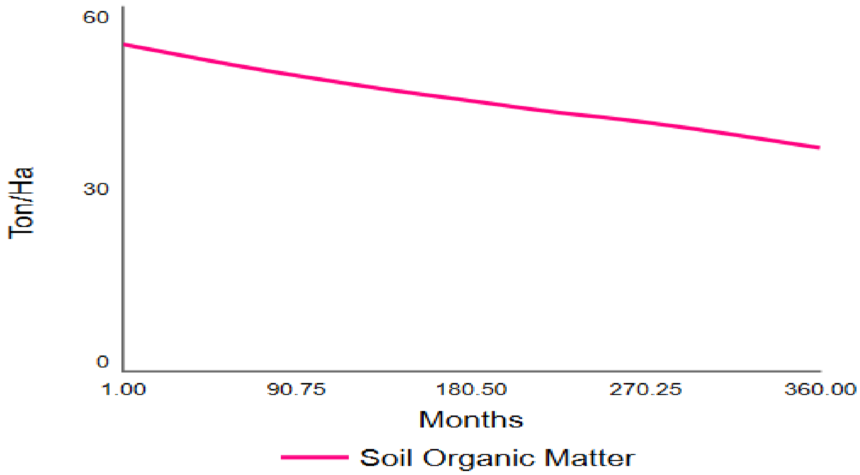


Figure 39 (a): Simulated Soil organic matter (SOM)

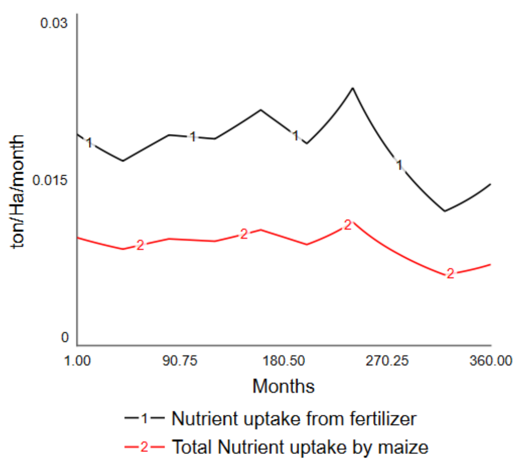


Figure 39 (b): Nutrients uptake from fertilizer& total nutrients uptake.

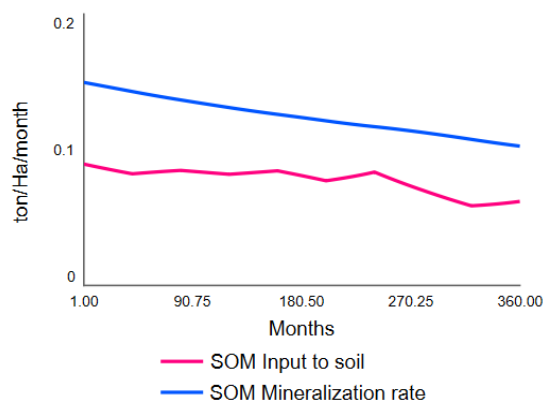


Figure 39 (c): SOM input & mineraliztion rate

Figure 39 (a-c) illustrates the simulated behavior of SOM, nutrient uptake from fertilizers, total nitrogen uptake, SOM input to the soil, and SOM mineralization rate. It is evident from figure 39

(a) that the SOM level in the field decreases over time due to uptake and use of SOM by the plants during the growing process.

6.1.3 Behavioral analysis of maize yield and maize production

This section describes the maize yield and production simulated behavior that depend on agriculture water availability and nitrogen uptake. Maize yield is calculated using the function of the effect of water on yield and the effect of nitrogen on yield. In this model, we calculated seasonal maize yield by using the seasonal counter and maize yield.

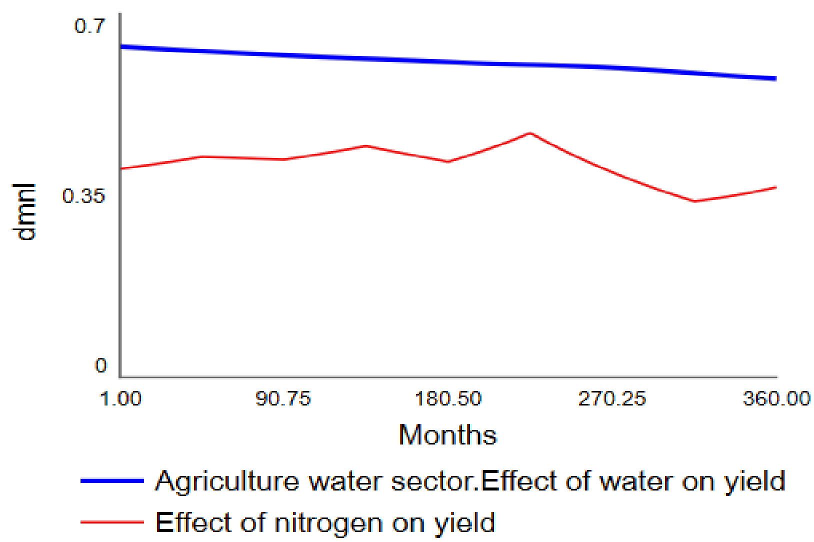
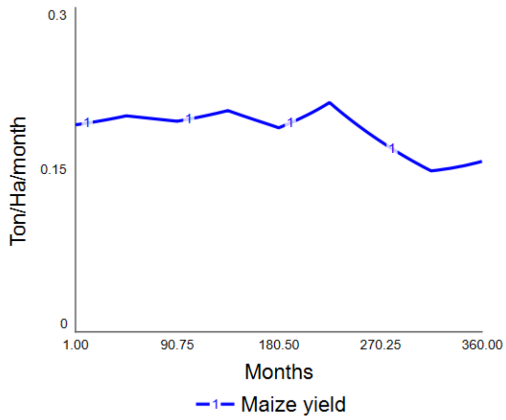


Figure 40 : Simulated effect of water on yield and effect of nitrogen on yield

Figure 41(a) and 41 (b) depict the behavior of the maize yield and maize production, which is characterized by substantial seasonal variation, and the yield fluctuates throughout the year.
Each year, total maize is harvested between April and July, but the maize yield spiked when the main harvest is collected. This phenomenon attributes to the oscillation between "plenty season" and "lean season" each year in Zambia [93].



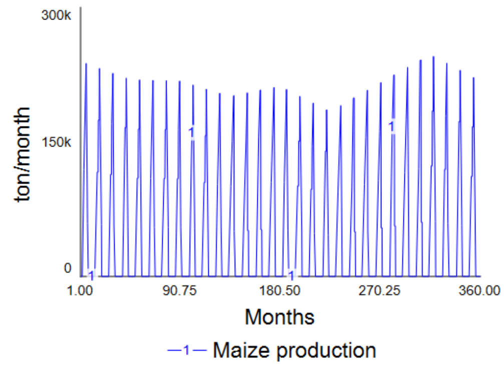


Figure 41(a): Simulated seasonal maize yield *Figure 41(b) : Simulated Maize production*

6.2 Behavioral analysis of Household free cash and Expenditure

In the small scale households economy, the income is provided mainly through sales of crops, mainly maize and other off-farm works, including selling livestock and handcraft objects [85]. The amount of free cash generated from the selling of crops depends on the selling prices and the quantities sold. The purchase of food items uses up 60% of the obtained free cash [47], and the rest is expended in other elements, which was only assumed in the simulation. The household can make a good profit and get a reasonable price, which is more than what they spend on fertilizer and soil improvement. Nevertheless, maize producer prices are currently in a negative trend due to increase supply [8]. A reasonable selling price affects the farmers' willingness to sell the product.

Figure 42 (a-b) illustrate the total income generated by small scale households from selling maize and other crops, showing that the behavior is fluctuating and following the same pattern as maize production because their income highly depends on it. In the model, the production of other crops was set to constant over time. The amount of maize sold fluctuated throughout the period as it depends on the seasonal maize availability.

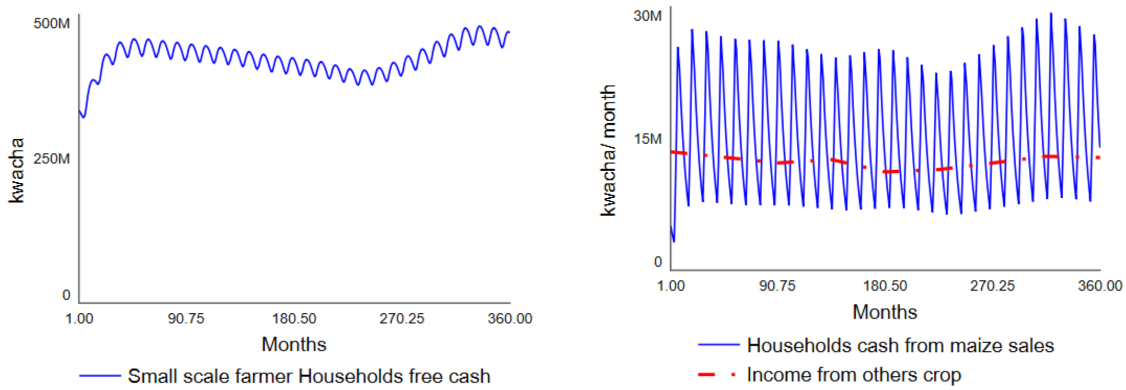


Figure 42 (a-b): Simulated household free cash

Figure 42 (c) shows the monthly expenditure trend throughout the calculated period, which fluctuates because small scale farmers income mostly depends on seasonal maize production. The behavior of expenditure on food follow similar pattern over time.

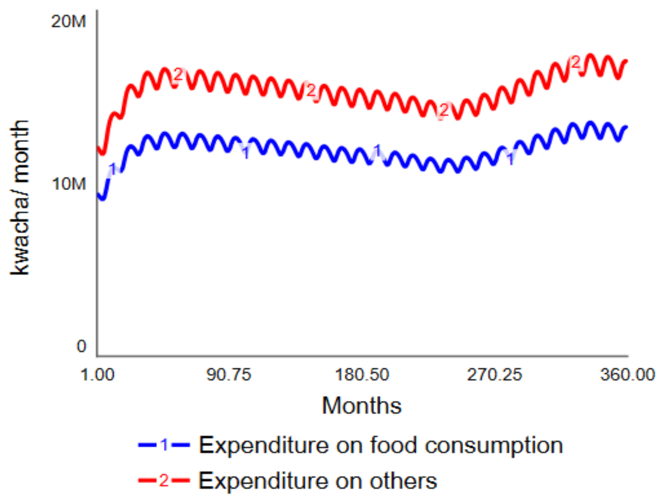


Figure 42 (c): Simulated household expenditures.

6.3 Behavioral analysis of Small scale farmer households food insecurity

This chapter focuses on the simulated behavioral interaction between various variables resulting in the existing behavior of undernourishment and food deficit. The population is a crucial parameter in any food systems model, as it directly influences total food demand and food consumption. Here, it explains the behavioral analysis of desired and actual kcal consumption from maize, which ultimately results in the prevalence of undernourishment and food deficit.

Figure 43 shows the total population and small scale farmer households have grown exponentially in a similar pattern because the number of small scale farmers is generated from multiplying the percentage with the population. The total population in 2010 was13.6M, which is expected to rise to 32M at a population growth rate of 2.87 for 360 months [2].

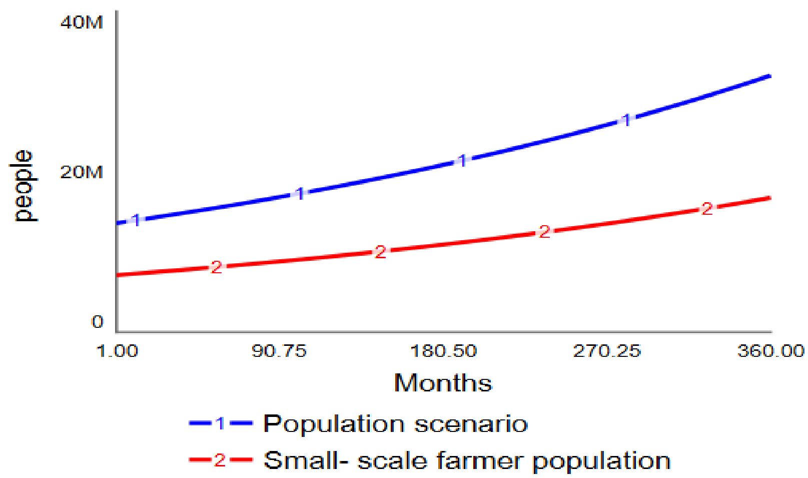


Figure 43 : Simulate population scenario and small- scale farmer population.

Figure 44 (a) shows the desired Kcal requirement per-capita, which is increasing exponentially as the population is growing steadily. Nevertheless, the actual kcal consumption is oscillating with a steady trend throughout the period , which create a gap between desired and actual Kcal consumption because it is obtained from the function of seasonal maize production.

Figure 44(b) illlustrates the behavior pattern of the actual population nourished and desired nourished population. Desired nourished population is gradually increased it is a function of daily per capita kcal requirement multiplied with small-scale households population.

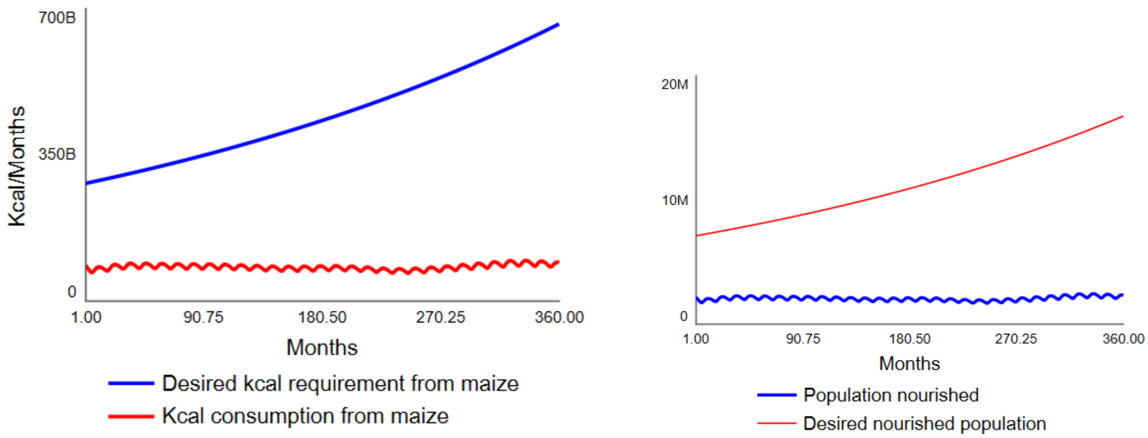


Figure 44 (a-b): Simulated behavior of desired and actual Kcal requiremen, desired and actual nourished population

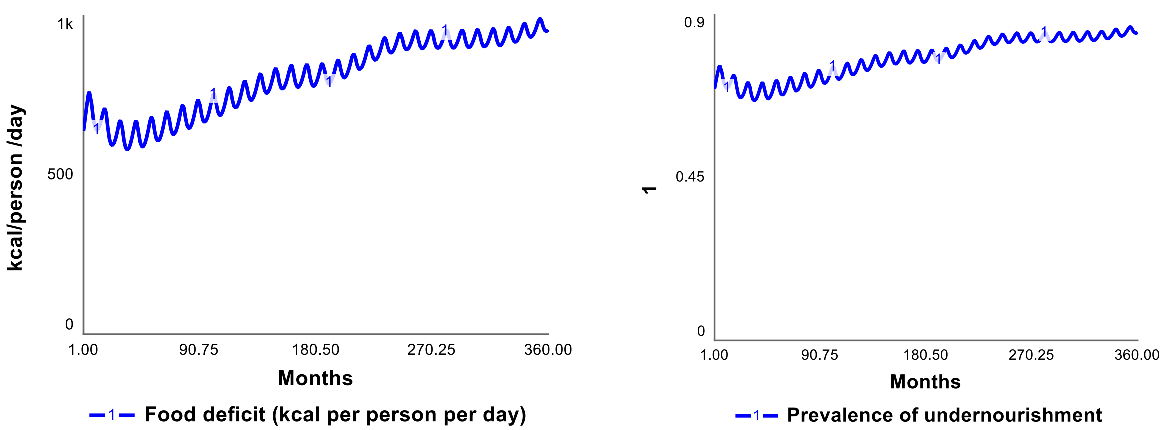


Figure 45(a-b): Simulated food deficit and prevalence of undernourishment
Fig 45(a,b) are showing increasing oscillating behavior throughout the period

The behavior analysis for physical access of maize, together with the desired kcal requirements enables us to examine the behavior of the actual kcal consumption, which results in the behavior of prevalence of undernourishment and food deficit.

6.4 Policy analysis & Testing

This chapter will focus on using the knowledge from the previous chapters to formulate future policy options and analyze scenarios on certain variables. Our simulation model shows that post-harvest food loss, household income, soil fertility and maize yield are crucial factors to food insecurity. Therefore, our model primarily aimed to design interventions that can increase maize production and reduce post harvest loss, improve household economy thereby improving food security among small-scale household farmers in Zambia.

6.4.1 Policy option analysis

Five policy options; more access to fertilizer, post-harvest storage management, organic matter addition through conservation agriculture with remaining more plant residues, intercrop interventions, and livestock poultry farming are the main future policy options that will be considered to improve the household food security in Zambia. However, the policy options are made for demonstration and a better understanding of their potential outcome of the problem and do not represent the actual policy options. For practical application, the viability requires a more precise assessment from policymakers and relevant stakeholders.

6.4.1.1 Policy option 1: Zero post-harvest loss

Post-harvest food loss is one of the weakest points in the production – consumer supply chain. This can happen at various levels, from the delayed collection of maize from the depots, poor storage, and lack of proper facilities. Globally, about one-third of the food produced is lost or wasted each year [94], which is around 30-40 percent in Zambia[95]. FAO suggests several post-harvest management technologies to reduce post-harvest food waste, including the Purdue Improved Crop Storage (PICS) bags, hermetic bags, metal and plastic hermetically-sealed silos, and tarp and candle equipment [96]

In figure 46, the green part shows the stock and flow structure of the post-harvest loss policy. When the desired share of PHL value is zero as one of the proposed policy options, reducing post-harvest loss will increase food availability and reduce the food-deficit among small scale farmer households.

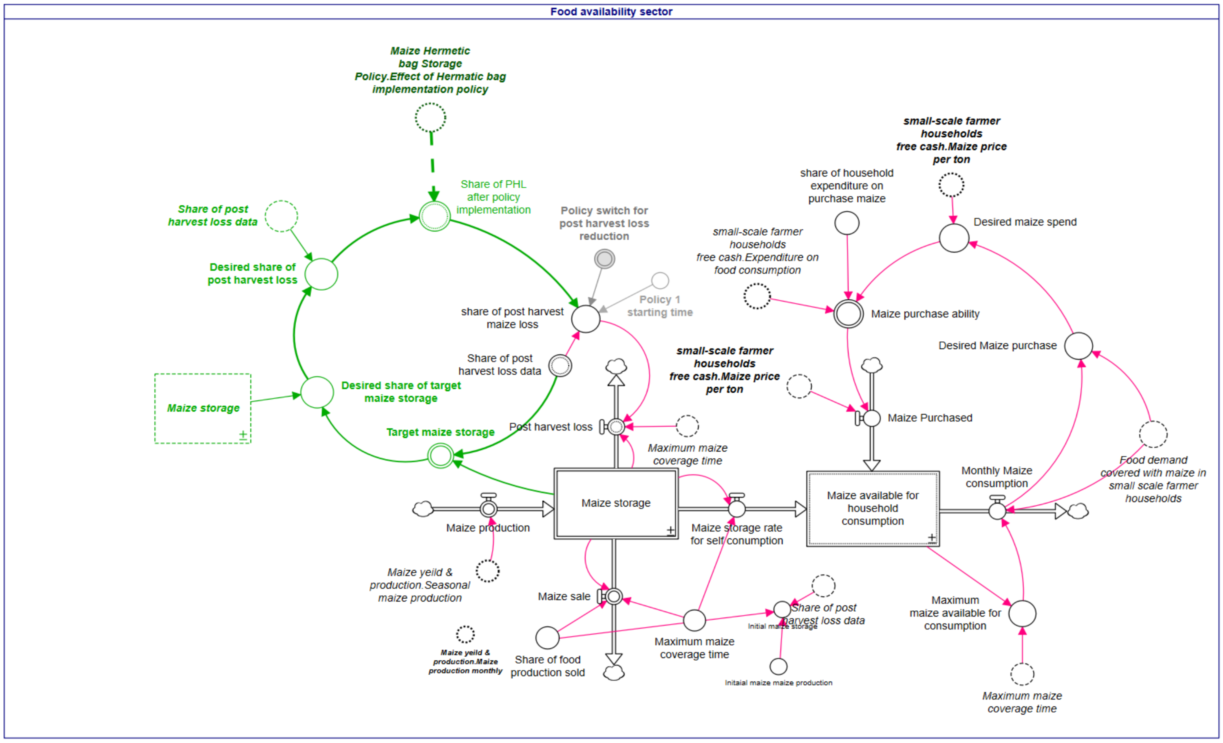


Figure 46: Stock and flow structure (SFD) of the Post harvest loss policy (Green part)

Figure 47 shows the stock and flow structure of Zero post-harvest loss policy implementation using hermetic storage bags for maize storage.

Hermetic bags are air-sealed; therefore are ideal for the storage of grains and seeds. They are cost-effective, therefore the cost can be has taken from the share of fertilizer subsidies input. Figure 47 shows the SFD of the cost-effectiveness analysis that shows the relative cost of hermetic storage bag policy implementation and the zero post-harvest loss policy outcome.

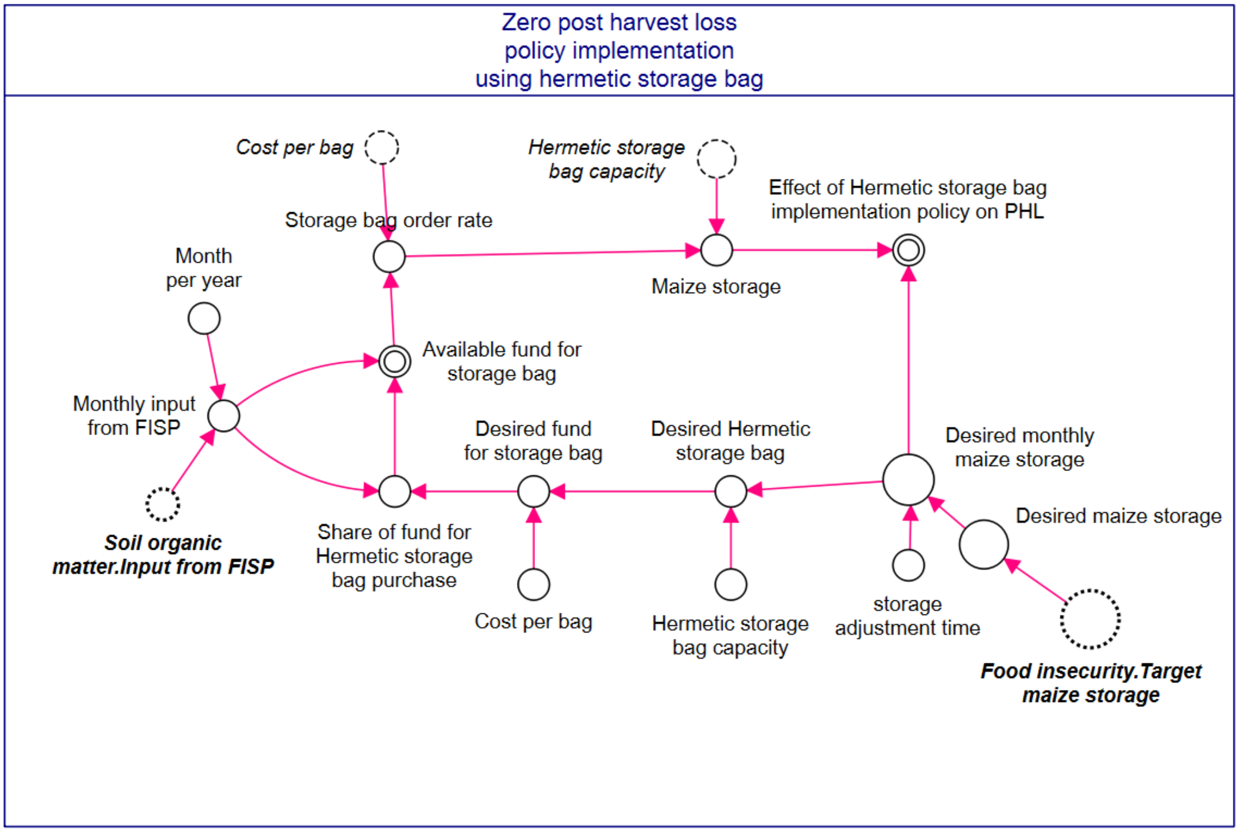


Figure 47: SFD of the zero post-harvest loss policy implementation using hermetic storage bag.

Figure 48 shows that the stocks and flows of cost-effectiveness analysis.NPV of maize storage cost is calculated by following equations:

NPV_Of_Maize'_STORAGE_COST(t) = NPV_Of_Maize'_STORAGE_COST(t - dt) + (Change_of_NPV_Maize_STORAGE_COST) * dt

INIT NPV_Of_Maize'_STORAGE_COST = 0

UNITS: kwacha

DOCUMENT: Net present value is a financial model that calculates the net value of a project today by discounting future cash flows over the lifetime of a project by an opportunity cost of capital. This stock calculated the future return on this policy investment.

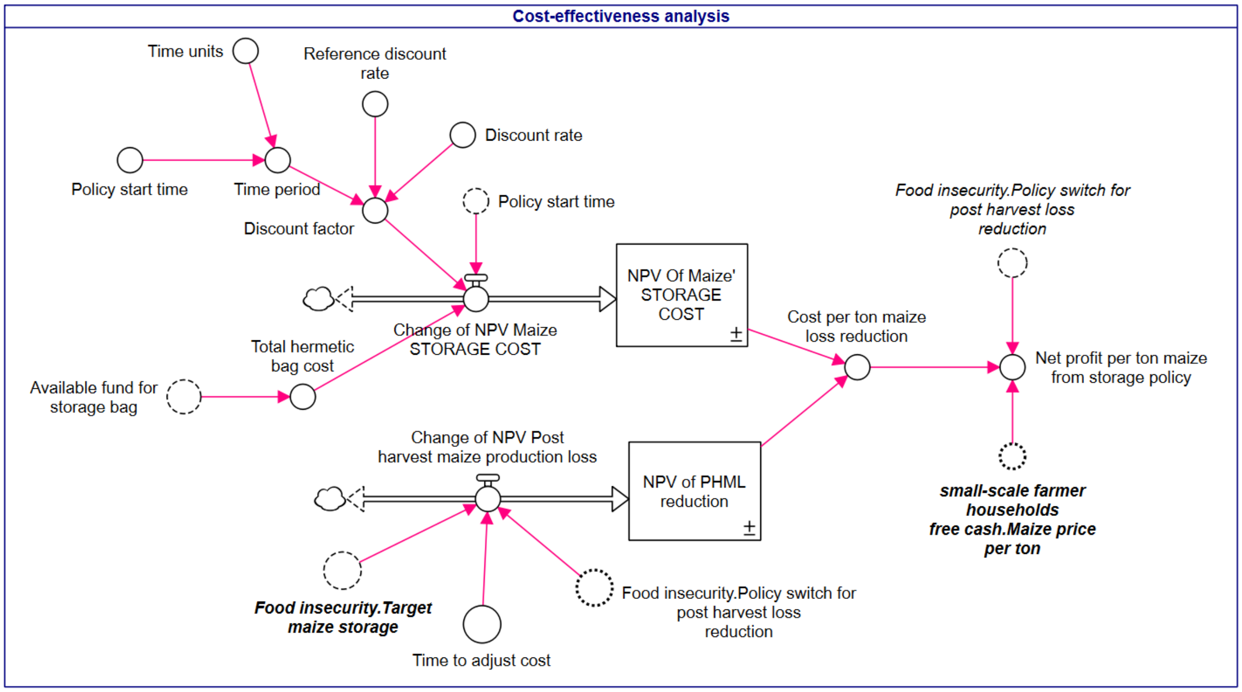


Figure 48: SFD of cost-effective analysis of zero post-harvest loss policy.

6.4.1.1.1 Policy leverage points and behavior analysis of Zero post-harvest loss policy

The policy options analysis is simulated with the base run conditions and compared to the simulations generated by adding zero post-harvest loss policy options into the model.

When we turned the policy switch on for policy option one; it shows that simulated behavior of maize storage and maize sales started to increase than base run with the same pattern from the policy starting month 144 (the year 2021) till the end (the year 2040) in the following figure 49 (a-b).

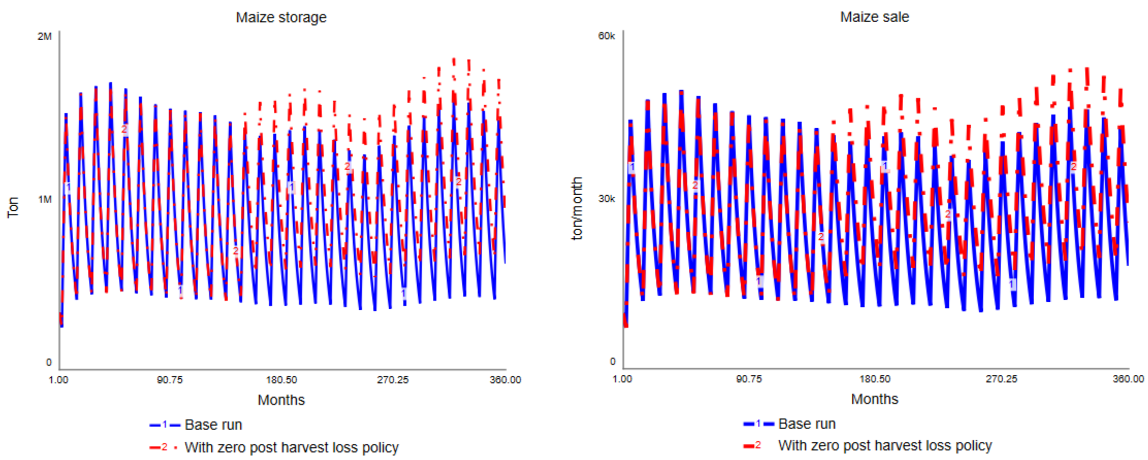


Figure 49 (a-b): The behavior analysis of maize storage and maize sales with policy option one.

Figure 50 (a-b) shows the household income from maize sales and fertilizer expenditure, both of them increased with zero harvest loss policy compared to the base run from the policy starting time 144 months till the end. We can say that the first policy increased maize sales and has a positive effect on the household's income leading to more investment in private fertilizer expenditure.

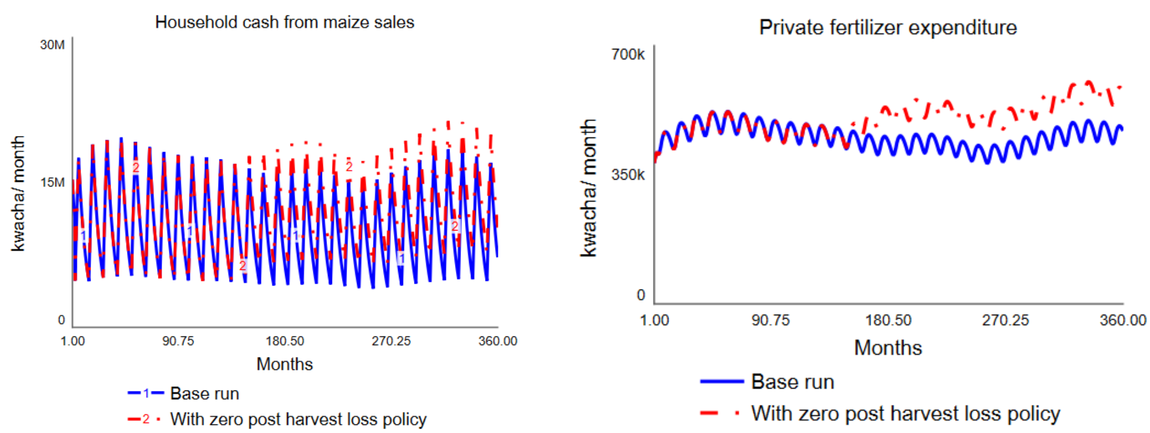


Figure 50 (a-b): The behavior analysis of household cash from maize sales and private fertilizer expenditure with policy options one.

Figure 51(a-b) shows that the zero post-harvest loss policy option did not affect the fertilizer subsidies significantly although the cost of implementation of storage was subtracted from the input of FISP. Fertilizer subsidies decreased to 1ton/month, which has an insignificant effect on soil organic matter (SOM) because of increased private fertilizer expenditure with this policy. Therefore, the behavior of the system follows the same pattern as the base scenario.

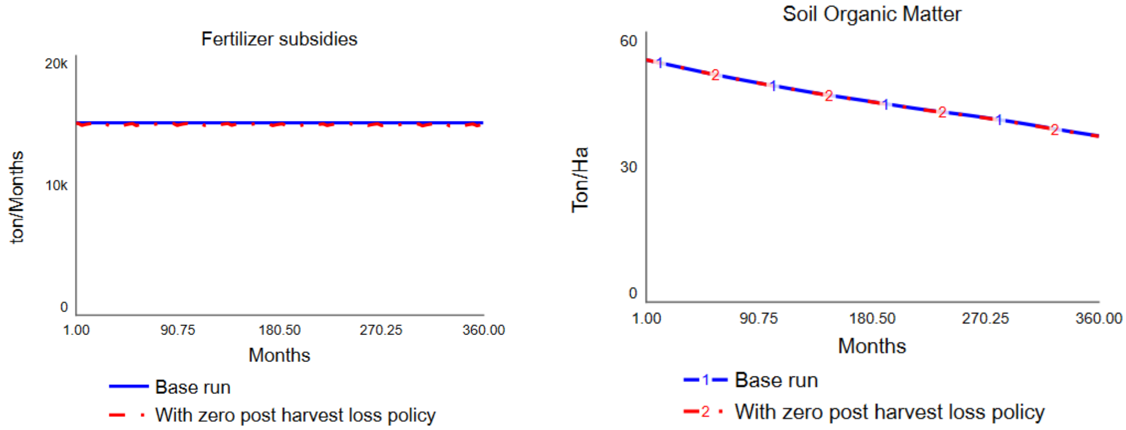


Figure 51 (a-b): The behavior analysis of fertilizer subsidies and SOM with policy options one.

Similarly, figure 52 (a-b) illustrates the behavior of maize purchase ability and kcal consumption from maize after applying the zero post-harvest loss policy. There is a significant increase in household income than the base scenario that improves the maize purchase ability for small scale farmers that will help them to access more kilocalorie intake in the future. On the other hand, intervening in the system with this policy reduces the food deficit and prevalence of undernourishment (PoU).

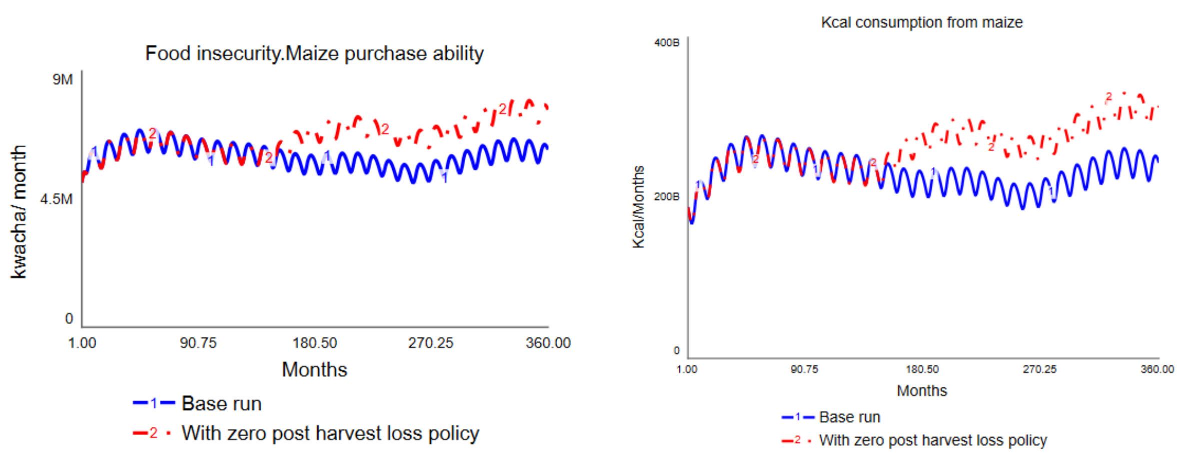


Figure 52 (a-b): The behavior analysis of maize purchase ability and kcal consumption from maize with policy options one.

The implementation resulted in an increase in small scale farmers' access to kcal consumption and a decline in food deficit and PoU among farmers from the month 144 month till the end in the momth 360 as shown in figure 53 (a-b).

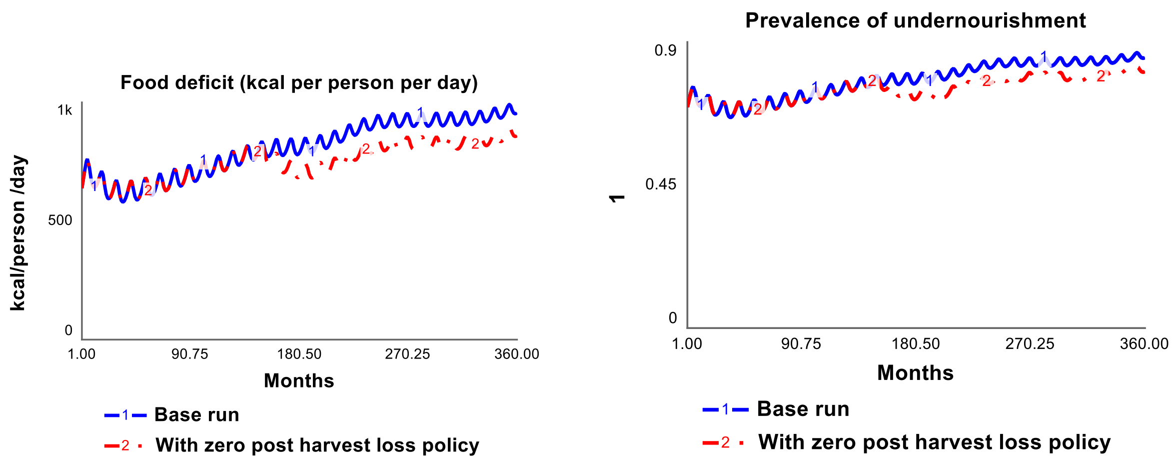


Figure 53 (a-b): The behavior analysis of food deficit and PoU with policy options one.

Implementation of zero post-harvest will reduce food deficit, ensure food security and increase cash flow among the small scale household farmers in Zambia. The study also points the detrimental economic effect of post harvest food loss that hinders food availability and increase the food price [97]. Finally, the study suggests that the farmers will arrange a better storage option for ttheir their maize to avoid losses.

6.4.1.1.2 Model output of cost-effectiveness analysis of using hermetic storage bag

Cost-effectiveness analysis whether zero harvest loss through application of hermetic storage bags is feasible or not. It compares the zero post-harvest policy to the base run scenario by estimating how much it costs to gain per ton maize storage. From the figure 54, we can see that there is no profit with a base run the value is zero till starting the policy which increased the profit after deduction maize storage cost implementing the zero post-harvest loss policy.

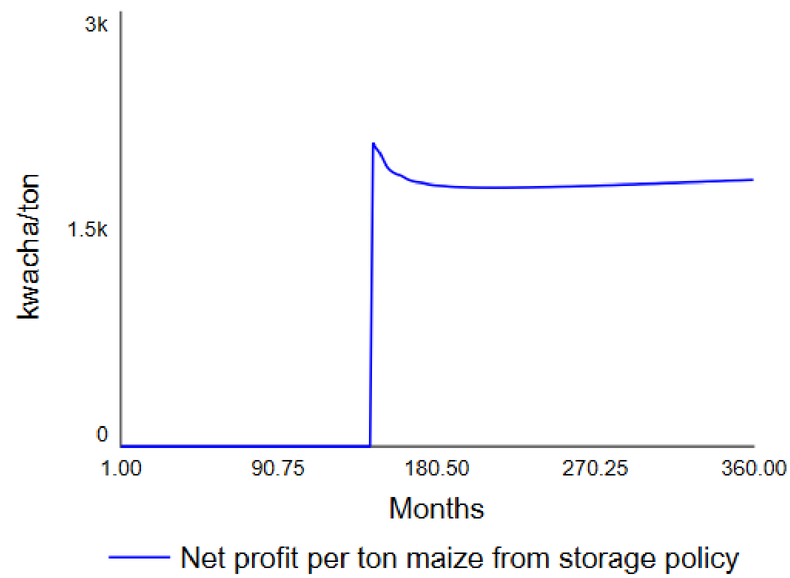


Figure 54 : Model output of cost-effectiveness analysis of using hermetic storage bag.

6.4.1.2 Policy option two: More access to fertilizer

The use of fertilizer in Zambia has increased steadily since 2010/11. Governmental fertilizer subsidies of the most important factor behind this rise, which makes up 61 percent of total fertilizer use. However, there is ample scope for improvement of the sitation, only 39 percent of Zambian smallholders use inorganic fertilizer at the national level [2].

Nevertheless, small-scale farmer households have limited access to the FISP than the national level, thus they are more prone to poor food production and food insecurity. Figure 55 shows the causal loop diagram (CLD) of second policy, showing that an increase in FISP will initiate a positive feedback loop among SOM, maize production, household free cash, and private fertilizer use. The main aim of this policy is to boost maize production through an increase in fertilizer subsidies. As estimated, subsidizing more fertilizer significantly contributes to a high amount of nitrogen that results in increased yields, which improves the availability of food, thus allowing the small scale farmers to consume and sell the Maize. At the same time, they can utilize the earned money to purchase food in lean season if necessary. To summarize, high fertilizer application significantly increases the availability of food among the small-scale farmer households in Zambia.

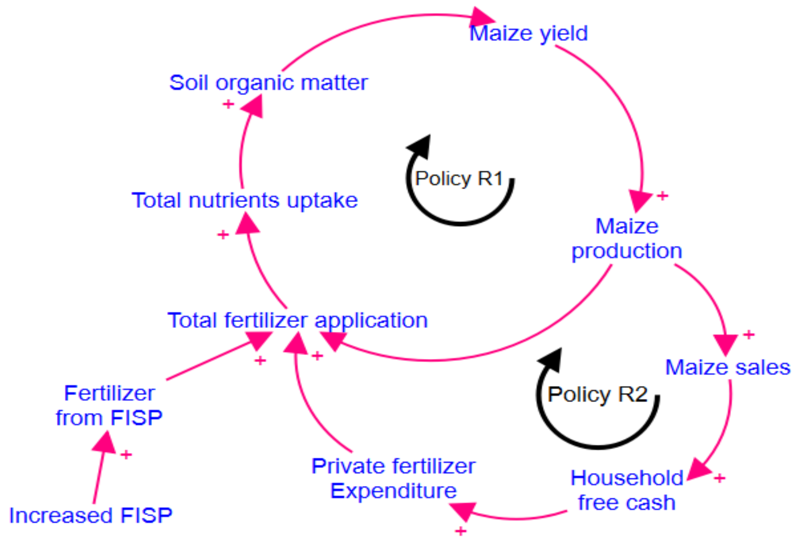
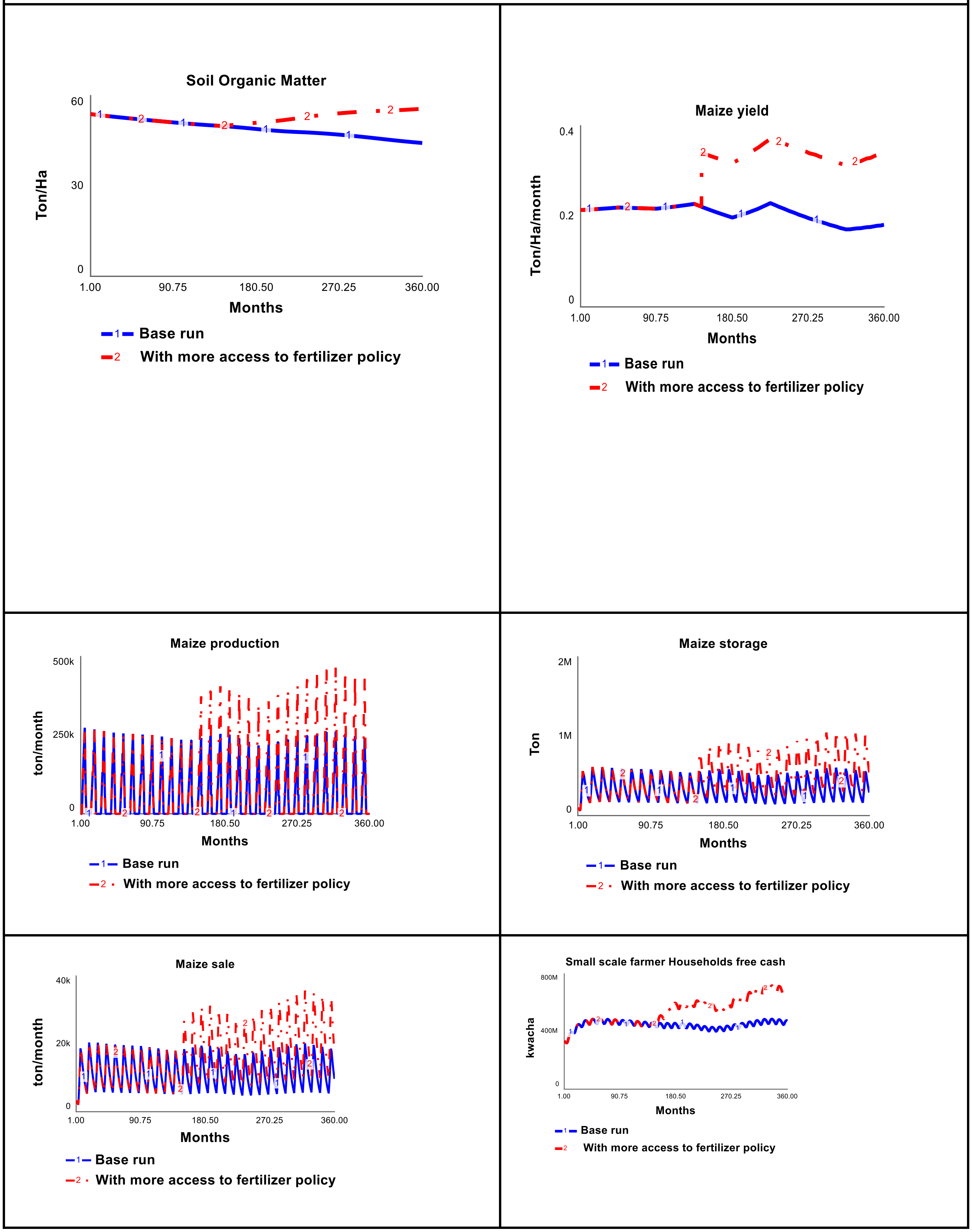


Figure 55 : CLD of more access to fertilizer subsidies policy

6.4.1.2.1 Policy leverage points and behavior analysis with more access to fertilizer policy

Simulation data estimated the amount of yield can be generated by increasing fertilizer subsidies. Table 6 shows the effect of intervention of second policy; SOM and maize yield increased in first 144 months, after that it is constant over time. With the increase in the maize yield, maize production, maize storage, maize sales, household income, private fertilizer expenses also increased in a similar pattern compared to the base run scenario. Similarly, kcal consumption from maize also increased, which causes an decline in food-deficit and prevalence of undernourishment (PoU). To conclude, The model hints that an increase in fertilizer application improved household food security for few years initially. But the soil fertility will decay in the following years due to use of chemical fertilizer for a long time.

Simulation result from more access to fertilizer policy



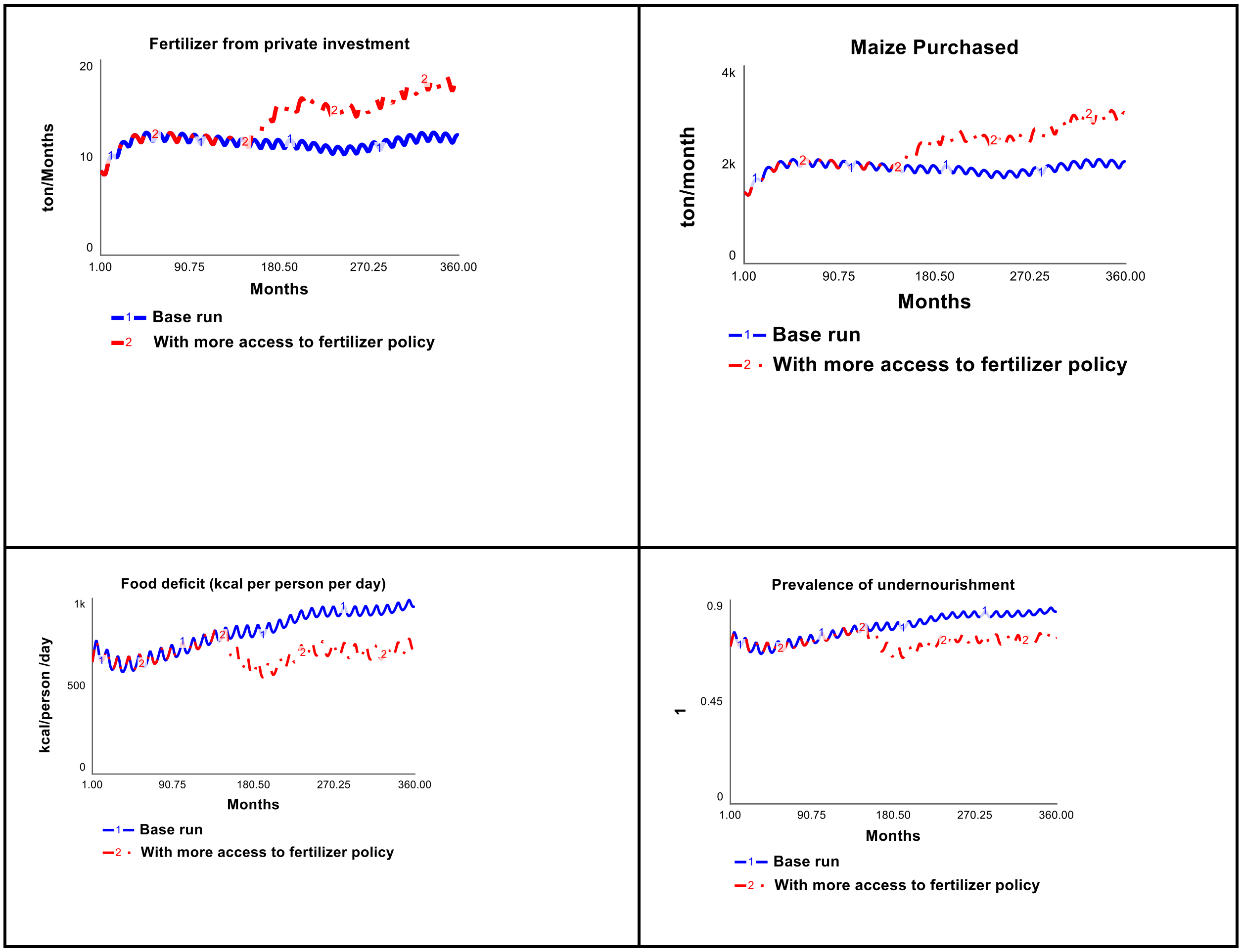


Table 6: Model output from more access to fertilizer policy

6.4.1.3 Policy option three: Organic matter addition from maize intercrop intervention

The third suggested policy in this study is intercrop intervention. Studies recommended that the gliricidia/maize intercrop significantly improve the Maize yield upto two times [98]. Intercropping with sesbania, tephrosia, and gliricidia also revealed their effectiveness on soil fertility replenishment as they produces a very high-quality green manure and contain high quantity of nitrogen on their leaves [99, 100]. In the following figure of CLD, we can see intercropping causes an additive effect on SOM that increases the maize yield.

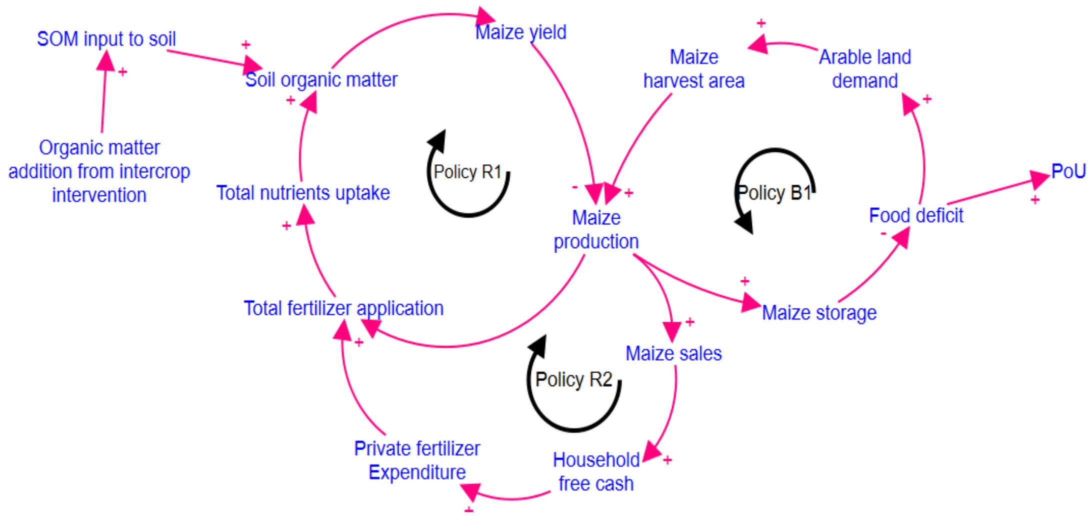
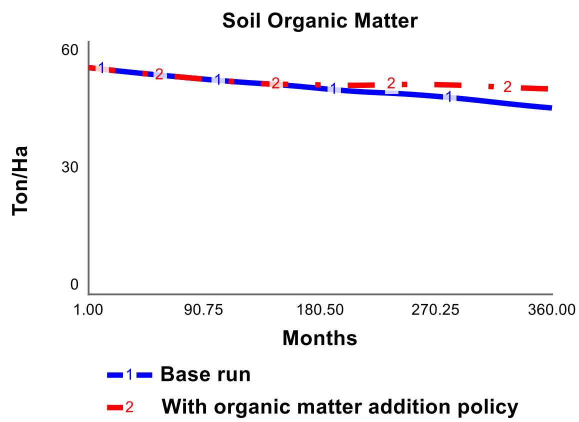


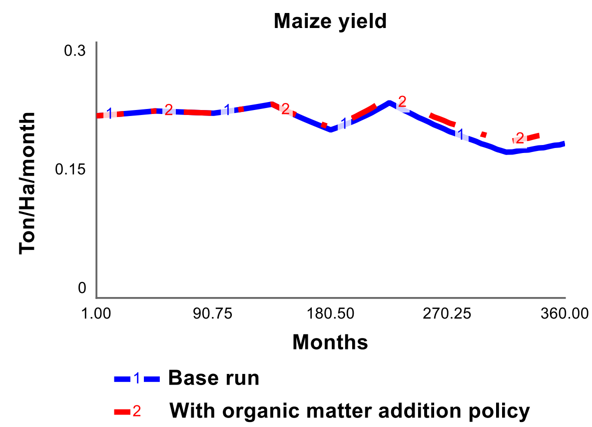
Figure 56: CLD of policy option three

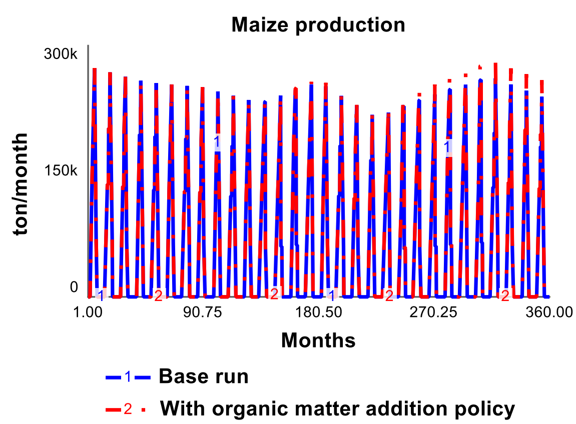
6.4.1.3.1 Policy leverage points and behavior analysis with Organic matter addition from intercrop intervention policy

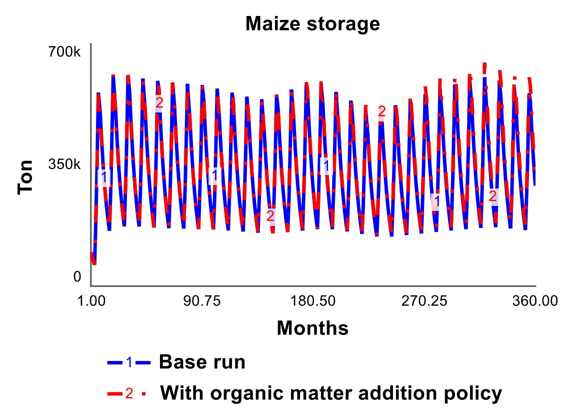
My current simulation shows that implementation of third policy will create increase the soil organic matter and maize yield , higher than the base run. Thus it suggests that intercropping causes addition of organic matter to the soil and an increase in maize production, kcal consumption from maize. Finally, it could reduce the PoU and food deficit among the small scale household level and enhance food insecurity among them.

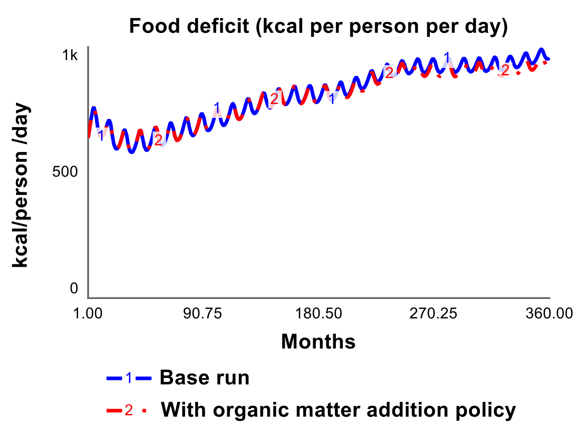
Simulation result from Organic matter policy options











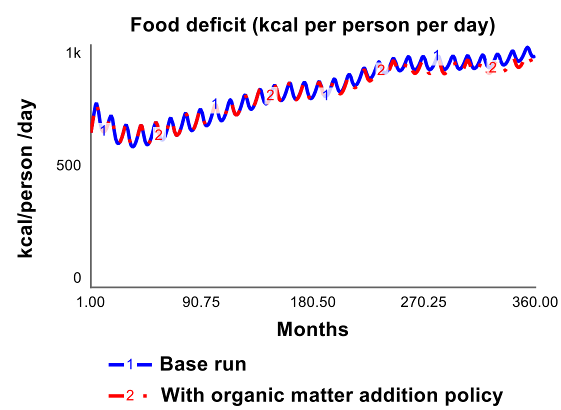


Table 7: Model output from policy options three.

6.4.1.4 Policy options four: Conservation agriculture with remaining more plant residues

The fourth policy of the model structure deals with removal of residues in the field. After harvesting, most of the farmers destroys maize plant residues through burning or animal feeding [101]. As described in the soil dynamics chapter, the plant residues go through mineralization and thereby improve the quality of the soil in the next season. The fertile land produces healthy plants and high maize yield [92]. Recently, conservation agriculture (CA), have been emphasized in Zambia, where the farmers are encouraged to prepare land using minimum tillage methods, intercropping, and retention of crop residues from the prior harvest [102] The following CLD of the policy option shows that there is an increase in soil fertility after increasing the share of plant residues.

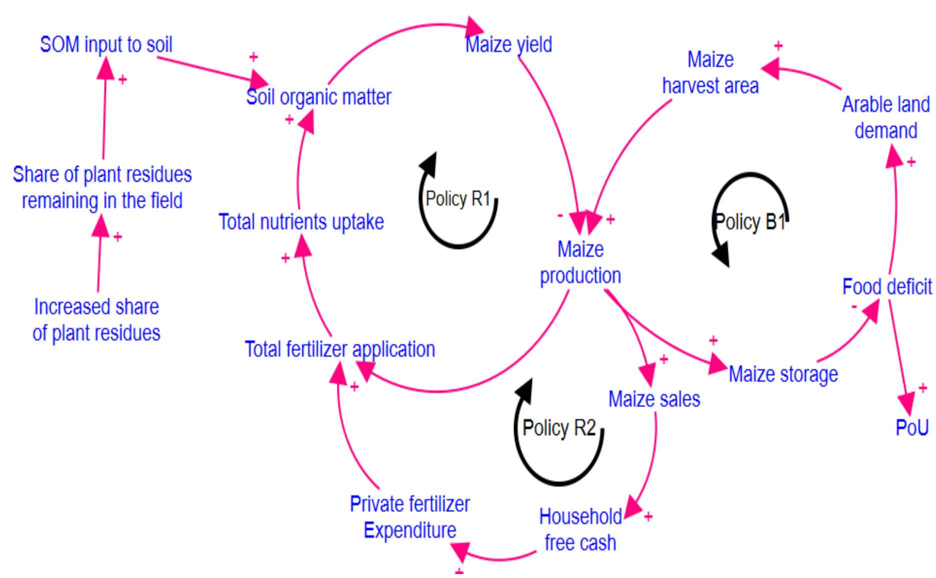
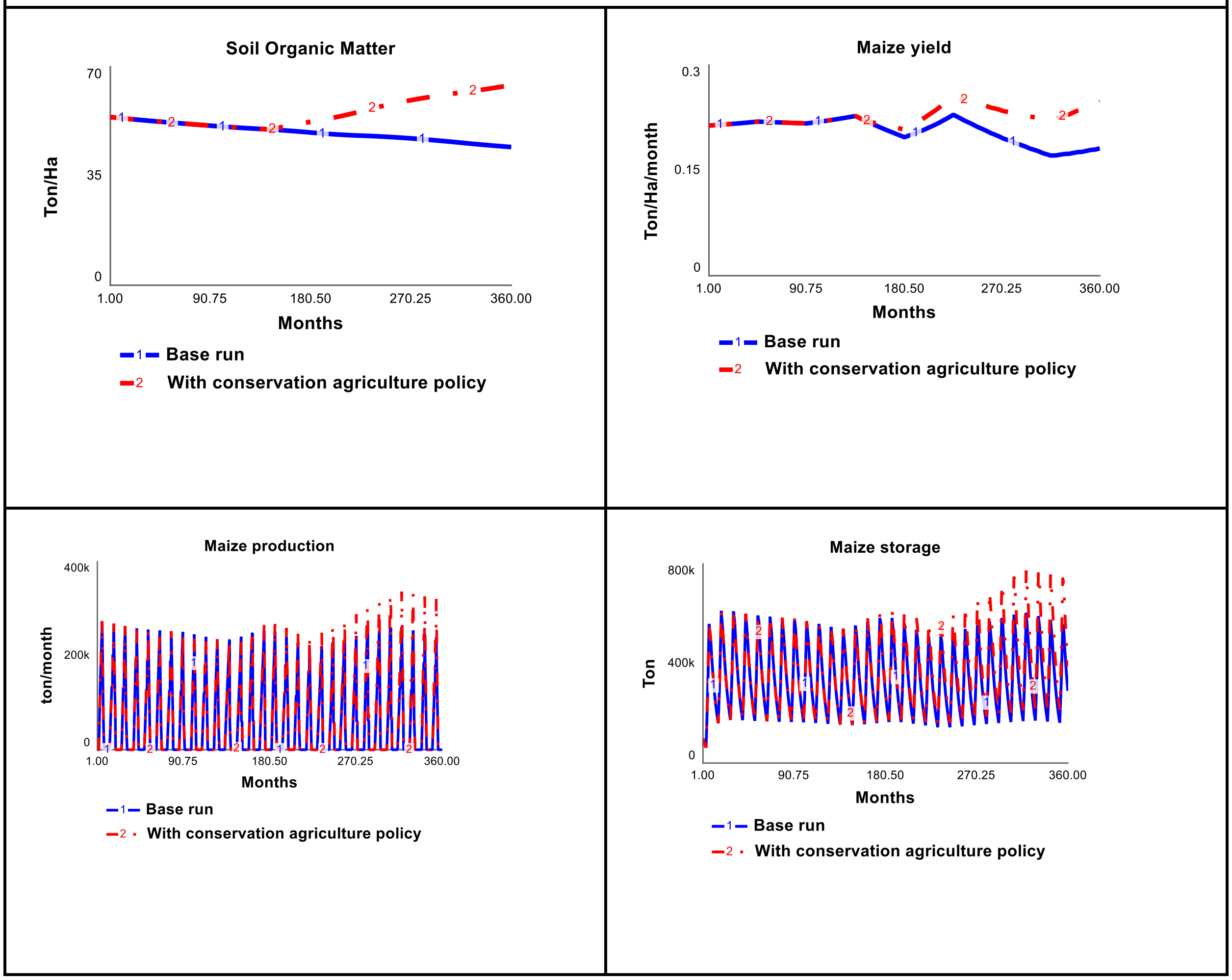


Figure 57: CLD of policy option four.

6.4.1.4.1 Policy leverage points and behavior analysis with conservation agriculture (CA) with increase plant residues in the field

Table 8 depicts the simulation results illustrating the interventions of conservation agriculture policy on soil organic matter. With conservation agriculture policy implemented, SOM increased steadily from the point of policy introduction until the end. At the same time, implementation of the fourth policy will increase maize production and yield, household income, maize purchase ability, investment in private fertilizer, and kcal consumption than the base run scenario. Therefore, it can be summarized that CA practice has a positive effect on maize yield, so small scale farmers should be informed and encouraged to practice it.

Simulation result from conservation agriculture



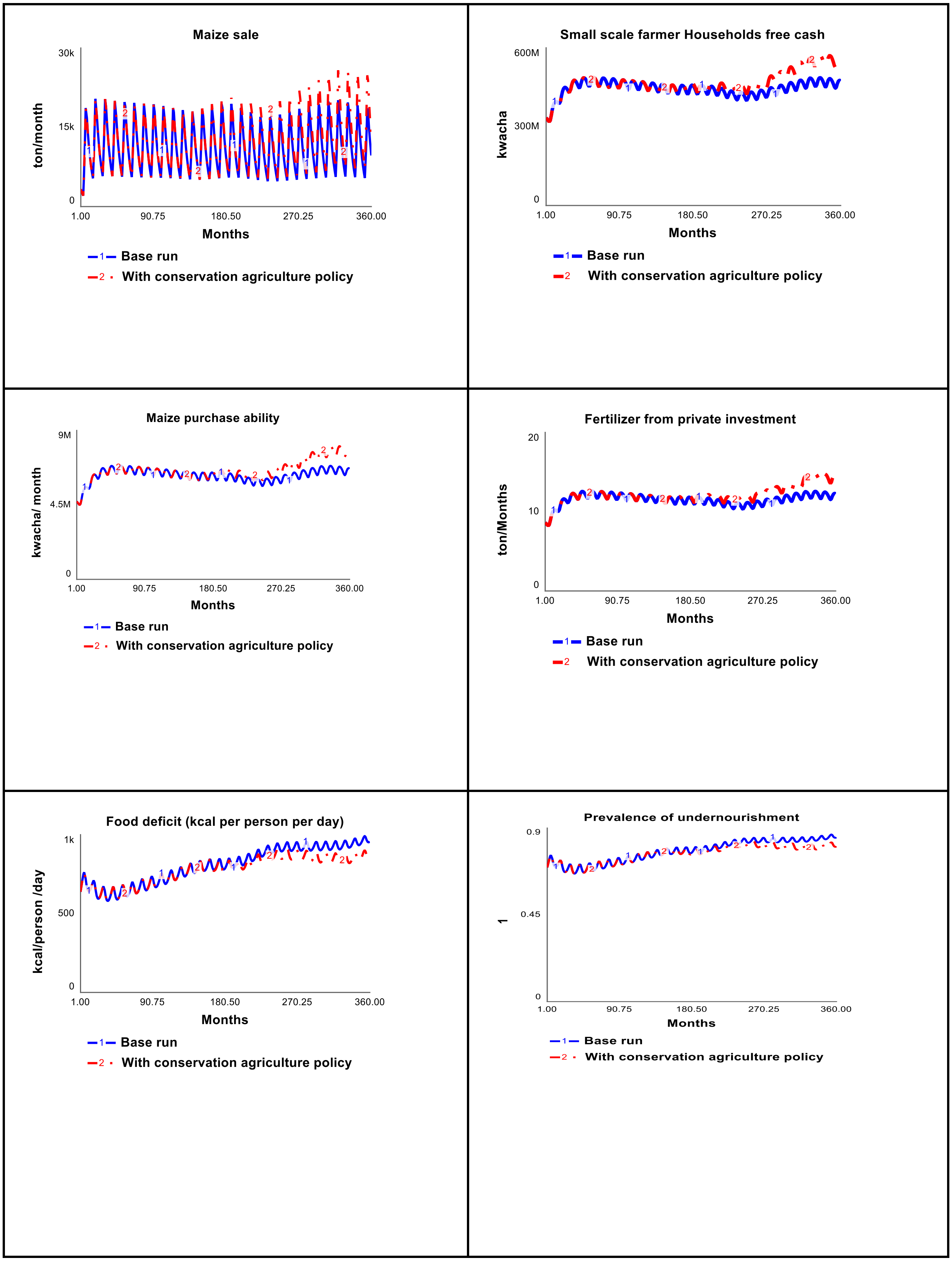


Table 8: Model output from CA policy options.

6.4.1.5 Policy Options five: Livestock (Poultry)

The livestock farming plays crucial role in generating income to smallholders, thus can be effective to come out of poverty and live a better life. Despite immense potential, the contribution of livestock sector to the national GDP is only 3.2 %. Besides an economic factors, they are source of dietary protein that is a necessary dietary component. The main purpose of livestock farming in Zambia is income generation which account for about 45% of the income by smallholder household [103]

In this food security model, livestock production was been added to the explanatory model. Nevertheless, it placed in the policy model as a probable policy to show the effect of intervention with livestock farming on food insecurity. Figure 58 depicts the stock and flow structure of livestock policy representing livestock (chicken) policy stock accumulate the chicken from livestock purchase input, livestock sold and death rate.

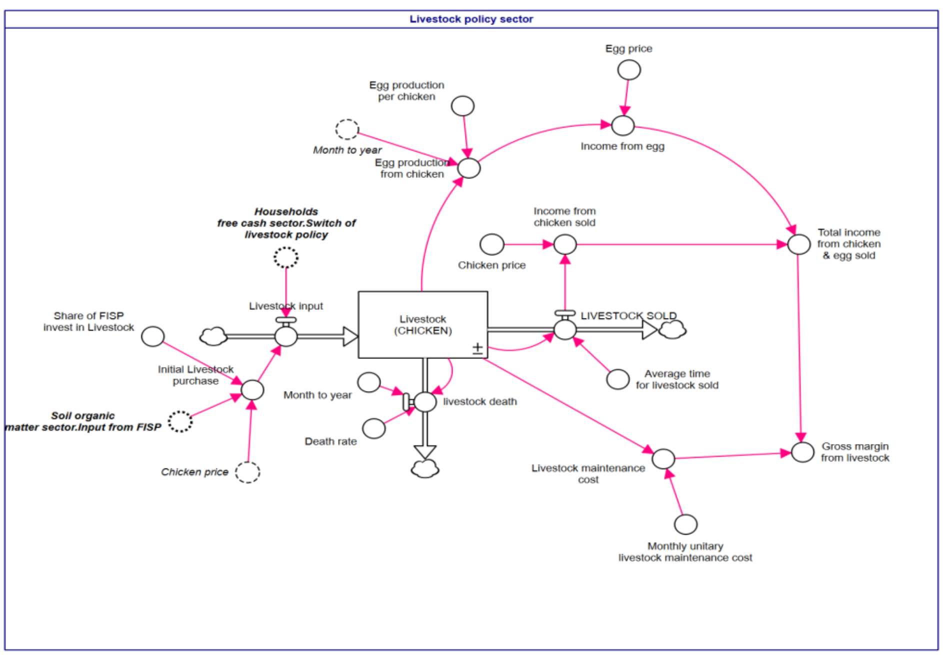


Figure 58: SFD of Livestock policy

The budget of implementation of this policy was taken from the 50% share of fertilizer subsidies. Therefore, deployment of this policy will result in reduction of fertilizer subsidies to half.

However, from selling of from egg and chicken, the farmer can generate income that can be used to buy other food, fertilizer or other necessities of the livelihood . Gross margin from livstock is calculated by the following equations:

Gross_margin_from_livestock = Total_income_from_chicken_&_egg_sold-Livestock_maintenance_cost

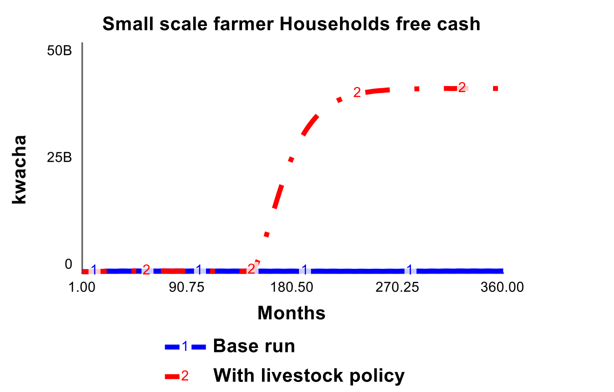
UNITS: kwacha/ month

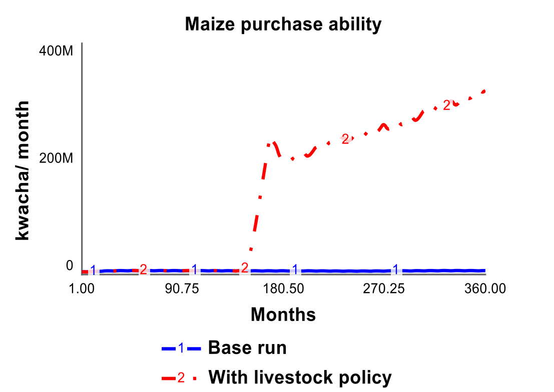
The small scale household farmers should be encouraged and to increase livestock production that can generate income, serve as a source of protein-rich food and the manuer is a good organic fertilizer to increase soil fertility.

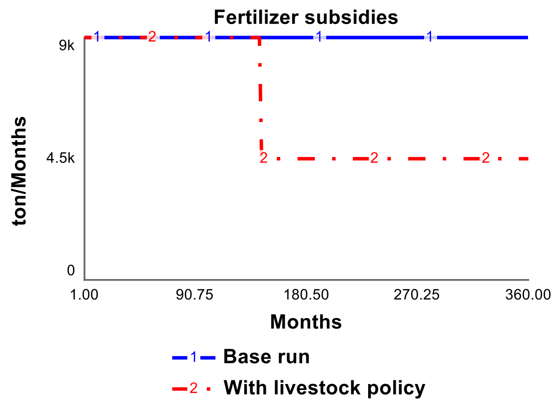
6.4.1.5.1 Policy liverege point and behavior analysis of policy option five

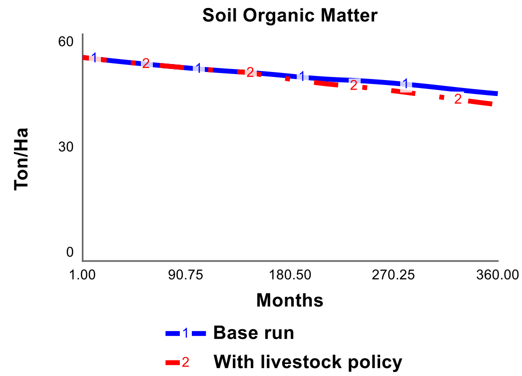
The simulated behavior of livestock policy illustrates that small scale farmer houshold income increased exponentially at first, followed by gradual stagnation until the reach an equilibrium level. With the increase of household income, maize purchased ability was also increased that leads to decline the food deficit and PoU to half than base run scenario. Moreover, implementation of this policy will cause reduction of soil organic matter, maize yield and maize production due to lower fertilizer accesss.

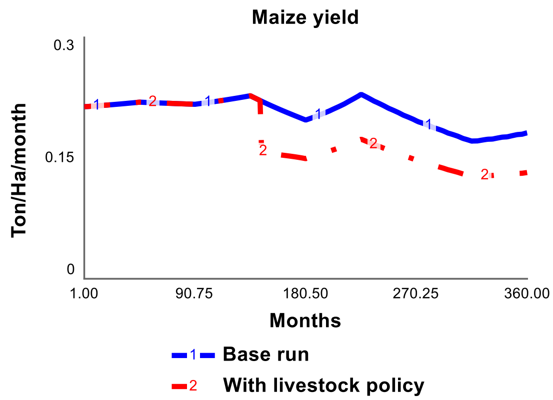
Simulation result from livestock policy

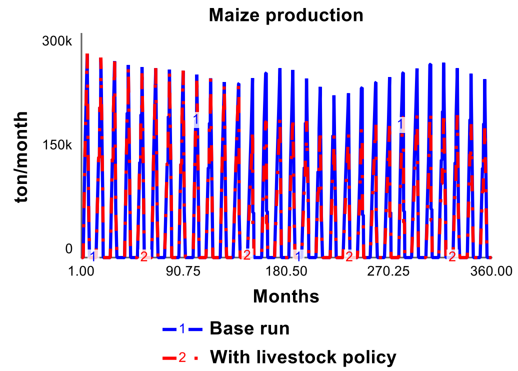


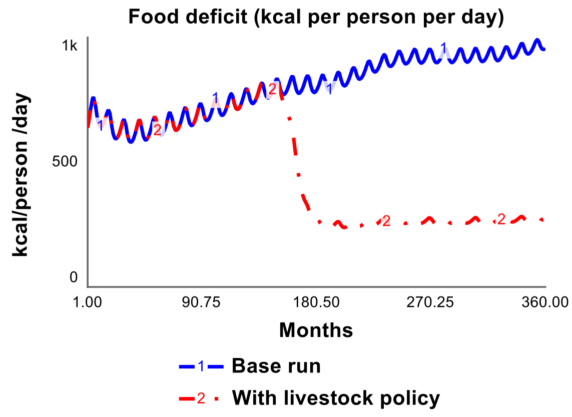












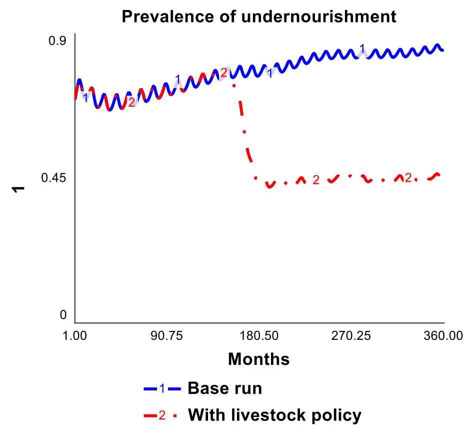


Table 9: Model output from more access to livestock policy

6.4.1.6 Combined with all five policy options

In this section we will illustrate the outcome behaviors of the main variables of the model by deploying all the recommended policy options on. Gaphical representations are given in this section which are shown in table 10.

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<tr><th colspan="2">Simulation results from combined all five policy options</th></tr>
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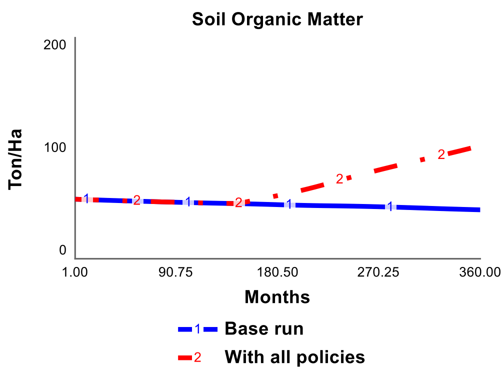

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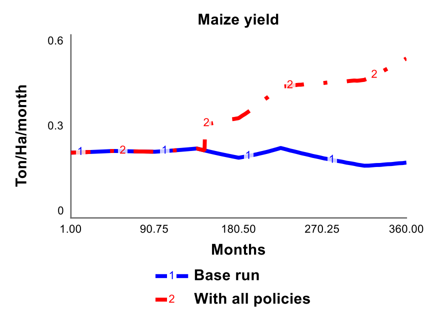

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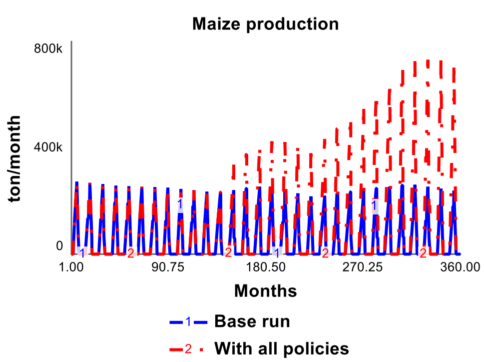

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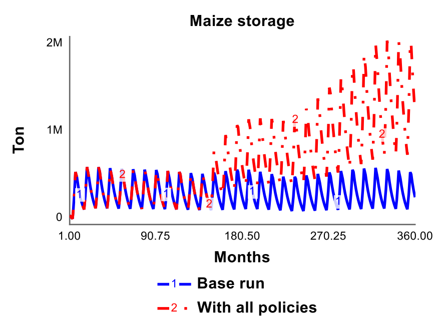

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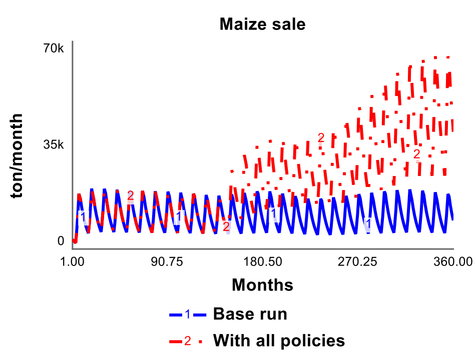

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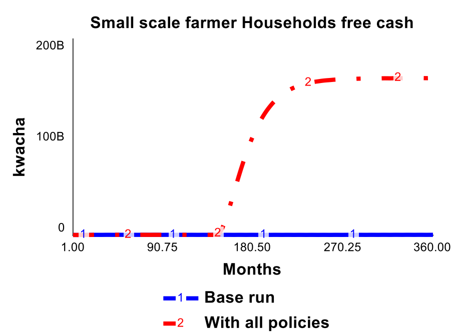

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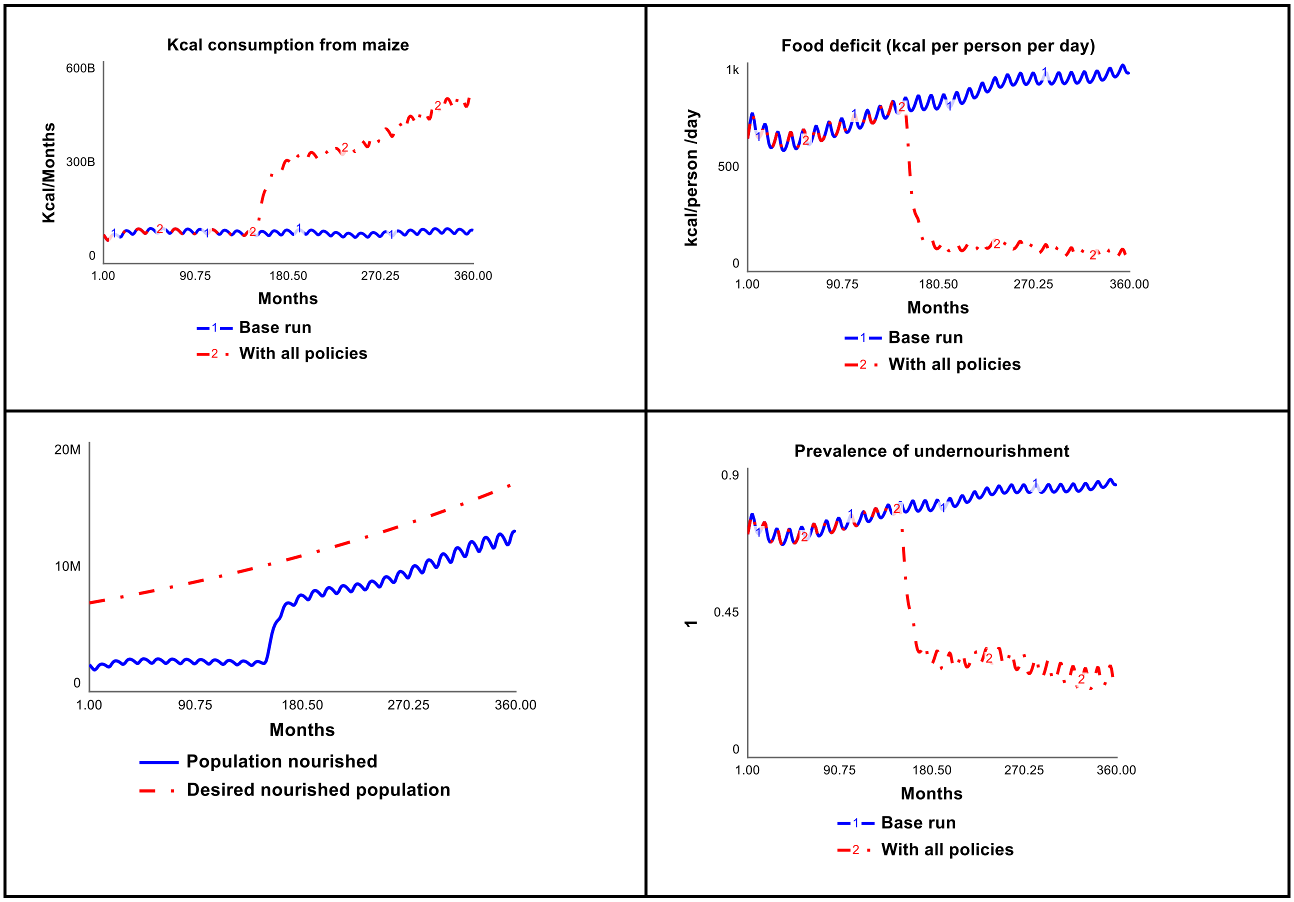

Table 10: Model output of all the policy combined

The simulation results show that all policies intervention, the SOM increased steadily from month 144 till the end. Moreover, increased SOM increases the maize yield drastically from the time of implementation, followed by slow increase till the end compared to base run scenario. The produced maize is stored properly so that it can be provide enough food for the whole year that decreases the demand for maize . The excess maize maize can be sold and contribute to household income. Thus, this study suggests that implementation of these policy options together can eradicate the household food security problem in the long run which is indicated in the figure by the food deficit and PoU declined to more than half compare to base run after intervention with all five policy options together.

7 Conclusion and recommendation

7.1 Major Findings of the research questions

In this chapter, we will summarize the significant findings, followed by the limitations and future perspectives of the study. This study aimed to understand the food insecurity problem among small-scale household farmers in Zambia. System dynamics modeling was used to unravel the complex dynamics between various variables to formulate policies to mitigate the problem. The behavior analysis of the food security model illustrates that the dependency on maize and its poor yield leading to food insecurity and poverty, restricting their ability to purchase food and spend for fertilizer, causing deterioration of maize yield in the next season and so on, thus forming a vicious cycle. The seasonal maize production frameworks were integrated into a causal loop diagram (CLD) that identifies several key variables: lack of irrigation, diminished soil fertility, and post-harvest loss. Therefore, the model indicated several policies for implementation: increasing fertilizer subsidies, reducing post-harvest loss through the use of the hermetic bag, and increasing soil fertility by applying conservation agriculture, which includes leaving plant residuals in the field and intercropping with other species. The model was validated through a range of tests to check the robustness and feasibility, proving that the model of the study is realistic and suitable for practical use. Deploying all the policies lead to an increase in soil fertility, maize production, and yield. Besides, the reduction of post-harvest loss is a highly sensitive, low-cost, and feasible policy option that increases the maize storage and other parameters to increase kcal consumption from maize. The policy of aiming zero post-harvest loss will increase maize availability from the year of implementation, affecting the supply-demand ratio in the market, leading to a low maize price, which is affordable for the people. Finally, the free cash obtained from the sale of crops allows them to spend more on agriculture. Lastly, from the simulation result, it is evident that the deployment of all the policies will result in food sufficiency among small-scale farmers in the future.

7.2 Limitation of the Study and Future Research perspectives

The model was built comprehensively to reflect the real system as much as possible. However, no model is ever perfect, and there are often several variables that should be extended, but which was not possible, not due to time limitation. Here are all the limitations of the and future perspectives of the current study. The model primarily focused on maize, which contributes to only 60% of the daily caloric consumption suggesting that other food crops should be included in the study to evaluate the overall agricultural production and total daily calorie consumption. Another limitation of the model is that it did not endogenously include the population scenario, which is a crucial parameter in any food system. The model should be extended and include population dynamics in the future. In many instances, data were obtained from secondary sources due to time constraints. To make the study more authentic and practical, primary data can be acquired in future studies. While calculating the expenditure on buying other things was exogenous, which has room for elaboration in further studies. Although the model suggested several policies for implementation, such as irrigation, it can improve maize production significantly.

Moreover, livestock farming can be an effective policy to improve the economic situation of small-scale household farmers that can supplement the agriculture sector. However, these policies were not elaborated in the model due to time limitations. In the implementation part, only the policy of reducing post-harvest loss was feasible, but the rest were merely wishful thinking. Lastly, an elaborated representation of poverty and health status could show the impact of policies on achieving the goals. Overall, this research laid the foundation for future work on increasing maize production and availability of food through the implementation of sustainable agricultural policies to ensure food security.

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Appendix

Model Equations and Documentation

Maize_yeild_&_production_sector:

Main_harvest_yield =

(Soil_organic_matter_sector.Maize_yield*Month_to_year)/Maize_harvest_month

UNITS: ton/Ha/month

DOCUMENT: This variable represents the harvest yield during the Maize harvest period that starts in April and ends in July.

Maize_harvest_month = 4

UNITS: Months

DOCUMENT: This constant variable represents the harvest month, and Household harvested Maize from April through July.The harvest is concentrated in the two peak months of May and June.

Maize_harvested_area =

Agriculture_land_sector.Arable_land*Share_of_Maize_harvested_area_for_small_scale_farmer

UNITS: ha

DOCUMENT: This variable represents the area on which Maize is produced.

Maize_production_monthly = Soil_organic_matter_sector.Maize_yield*Maize_harvested_area

UNITS: ton/Months

Month_to_year = 12

UNITS: Months

Seasonal_counter = COUNTER(1, 13)

UNITS: month

DOCUMENT: This constant variable represents the seasonal counter is used to calculate seasonal Maize production.

Seasonal_Maize_production = IF Seasonal_counter>=4 AND Seasonal_counter<5 THEN (Main_harvest_yield*Share_of_April_harvest*Maize_harvested_area) ELSE IF Seasonal_counter>=5 AND Seasonal_counter<6 THEN (Maize_harvested_area*Main_harvest_yield*Share_of_May_harvest) ELSE IF Seasonal_counter>=6 AND Seasonal_counter<7 THEN (Main_harvest_yield*Maize_harvested_area*Share_of_June_harvest) ELSE IF

Seasonal_counter>=7 AND Seasonal_counter <8

THEN(Main_harvest_yield*Share_of_July_harvest*Maize_harvested_area) ELSE

(Share_of_others_time*Main_harvest_yield*Maize_harvested_area)

UNITS: ton/month

DOCUMENT: This variable represents seasonal small-scale farmers Maize production that plays the main role in this food security model and it is the part of many feedback loops.

Share_of_April_harvest = 0.20

UNITS: dmnl

DOCUMENT: This constant variable represents the share of Maize harvest in April.

Share_of_July_harvest = 0.10

UNITS: dmnl

DOCUMENT: This constant variable represents the share of Maize harvest July.

Share_of_June_harvest = 0.40

UNITS: dmnl

DOCUMENT: This constant variable represents the share of Maize harvest in June.

Share_of_Maize_harvested_area_for_small_scale_farmer = GRAPH(TIME)

(1.0, 0.3540484928), (45.875, 0.3103619718), (90.75, 0.3160758824), (135.625, 0.2771888889), (180.5, 0.3171584211), (225.375, 0.2334643243), (270.25, 0.3046721053), (315.125, 0.3773536842), (360.0, 0.2857910526)

UNITS: dmnl

DOCUMENT: This constant variable represents the average share of arable land used to Maize produced.Data estimated from FAO.

Share_of_May_harvest = 0.30

UNITS: dmnl

DOCUMENT: This constant variable represents the share of Maize harvest in May.

Share_of_others_time = 0

UNITS: dmnl

Agriculture_water_sector:

Average_yearly_Precipitation = 1000

UNITS: mm/year

DOCUMENT: This constant variable represents the average scenario op precipitation that is taken up by Maize plants on one hectare throughout one growing season.

Source: .HarvestPlus Research for action (NO.5) September 2015.Maize Consumption Patterns and Consumer Preferences in Zambia (Hugo De Groote1*, Zachary Gitonga1, Earnest Kasuta2, Dorene Asare-Marfo3, and Ekin Birol)

Effect_factor_water_on_yield = 0.004

UNITS: year/mm

DOCUMENT: This variable represents the case specific constant of the Mitscherlich-Baule production function (which calculates Maize yields).It determines the strength of the reaction of Maize yields to a change in water uptake.

Effect_of_water_on_yield = 1-10^(-Monthly_effect_factor_of_water_on_yield*Water_plant_uptake)

UNITS: dmnl

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

Effect_slope_of_soil_organic_matter_on_water = 0.1

UNITS: dmnl

DOCUMENT: 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.

Indicated_water_uptake_share = Effect_slope_of_soil_organic_matter_on_water*Soil_organic_matter_sector.Relative_soil_organic_matter+Intercept_of_soil_effect_on_water

UNITS: dmnl

DOCUMENT: 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. (Johnston et al., 2009, Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes).

Initial_relative_soil_organic_matter = INIT(Soil_organic_matter_sector.Relative_soil_organic_matter)

UNITS: dmnl

DOCUMENT:

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

Intercept_of_soil_effect_on_water = Reference_water_uptake_share-Initial_relative_soil_organic_matter*Effect_slope_of_soil_organic_matter_on_water

UNITS: dmnl

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

Maximum_water_uptake_share = 0.5

UNITS: dmnl

DOCUMENT: This variable represents the maximum share of water that is taken up by Maize plants.

Minimum_water_uptake_share = 0.05

UNITS: dmnl

DOCUMENT: This variable represents the minimum share of water that is taken up by Maize plants.

Month_to_year = 12

UNITS: month/year

Monthly_effect_factor_of_water_on_yield = Effect_factor_water_on_yield*Month_to_year

UNITS: month/mm

Plant_uptake_share_of_water = MIN(MAX (Indicated_water_uptake_share,Minimum_water_uptake_share), Maximum_water_uptake_share)

UNITS: dmnl

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

Reference_water_uptake_share = 0.1

Soil_organic_matter_sector:

Soil_Organic_Matter(t) = Soil_Organic_Matter(t - dt) + (SOM_Input_to_soil - SOM_Mineralization_rate) * dt

INIT Soil_Organic_Matter = 53.8765

UNITS: Ton/Ha

DOCUMENT: This variable represents the stock of soil organic matter that is an important soil component that accumulates through the addition of biomass to the soil. Soil microbes and creatures decompose SOM through the mineralization process (Scheffer and Schachtschabel, 2010).

INFLOWS:

SOM_Input_to_soil = Plant_Residues+SOM_from_Livestocks+Nutrients_from_Animals_manure+STEP(Organic_matter_addition_from_intercrop_intervention, Start_time_of_organic_matter_intervention)*Policy_Switch_organic_matter_addition_2

UNITS: ton/Ha/month

DOCUMENT: This variable represents the addition of organic material to the soil. Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production. In addition a policy can be activated constituting a third source of organic matter through intercrop intervention and livestock.

OUTFLOWS:

SOM_Mineralization_rate = Soil_Organic_Matter/SOM_Mineralization_TIME

UNITS: ton/Ha/month

DOCUMENT: This variable represents the mineralization process of SOM and thus of its component nitrogen. (Scheffer and Schachtschabel, 2010).

Annual_FISP = 108000

UNITS: ton/year

DOCUMENT: Thus, this constant variable represents fertilizer subsidies from Government.In Zambai, Government has a policy program in place that fertilizer subsidies for farmers. These public programs can account for noteworthy shares on total fertilizer application. Data from worldbank.

Effect_factor_of_nitrogen_on_yield = 4.03

UNITS: ha*year/ton

DOCUMENT: This constant variable part of the Mitscherlich-Baule production function.

Effect_of_nitrogen_on_yield = 1-10^(-
Monthly_effect_factor_of_nitrogen_on_yield*Total_Nutrient_uptake_by_Maize)
UNITS: dmnl
DOCUMENT: This variable is an intermediate part of the Mitscherlich-Baule production function.It determines the strength of the reaction of Maize yields to a change in nitrogen uptake.
Effect_of_SOM_on_nitrogen_uptake = GRAPH(Soil_Organic_Matter)
(-10.0, 0.443), (0.0, 0.426), (10.0, 0.409), (20.0, 0.400), (30.0, 0.409), (40.0, 0.417), (50.0, 0.417), (60.0, 0.409), (70.0, 0.426), (80.0, 0.460), (90.0, 0.494), (100.0, 0.536), (110.0, 0.604), (120.0, 0.655), (130.0, 0.698), (140.0, 0.774), (150.0, 0.800), (160.0, 0.834), (170.0, 0.851), (180.0, 0.868), (190.0, 0.868), (200.0, 0.868)
UNITS: dmnl

Fertilizer_application = Fertilizer_from_private_investment + Fertilizer_subsidies
UNITS: ton/Months
DOCUMENT: This variable represents the total fertilizer applications of farmers.
Fertilizer_application_per_ha_Maize =
(Fertilizer_application/Maize_yeild_&_production_sector.Maize_harvested_area)
UNITS: ton/Ha/month
DOCUMENT: This variable represents the fertilizer applications per hectare Maize harvest area.
Fertilizer_from_FISP = IF (Policy_option_three_switch=1) AND (TIME >144) THEN
Monthly_fertilizer_subsidies+More_access_to_fertilizer_policy ELSE
Monthly_fertilizer_subsidies
UNITS: ton/month
Fertilizer_from_private_investment = IF
(Households_free_cash_sector.Switch_of_livestock_policy=1) AND (TIME>144) THEN 0
ELSE Private_fertilizer_expenditure/Fertilizer_price
UNITS: ton/Months
Fertilizer_price = 351660
UNITS: kwacha/Ton
DOCUMENT: This constant represents the average fertilizer price in real local currency per ton.

Fertilizer_subsidies = IF
(Households_food_insecurity_sector.Policy_switch_for_post_harvest_loss_reduction=1) AND(
TIME>144) THEN (Reduced_Fertilizer_from_FISP_with_PHL_policy) ELSE
Fertilizer_from_FISP
UNITS: ton/Months
DOCUMENT:
http://documents.worldbank.org/curated/en/481731468166490328/pdf/825080WP0ABIZa00Box379865B00PUBLIC0.pdf
Fertilizer Use
Government purchases under FISP (smallholder market):
2010/11 = 178,000 MT; 2011/12 = 183,000 MT
Increased_input_from_FISP = (108000+108000*0.5)/12
UNITS: ton/month
Increased_share_of_plants_residues_remaining_on_he_field = 0.85
UNITS: dmnl
Initiall_soil_organic_matter = INIT(Soil_Organic_Matter)
UNITS: ton/ha
DOCUMENT: This variable represents the organic matter in its initial value.
Input_from_FISP = Fertilizer_price*Fertilizer_from_FISP
UNITS: kwacha/month
DOCUMENT: In Southeast Africa, courtiers typically have a policy program in place that subsidises the purchase of fertilizer. These public programs can account for noteworthy shares on total fertilizer expenditure. Thus, this constant represents the public expenditure for fertilizer purchases (expressed in real local currency per year).
Maize_yield =
Effect_of_nitrogen_on_yield*monthly_Yield_plateau*Agriculture_water_sector.Effect_of_water_on_yield
UNITS: Ton/Ha/month
DOCUMENT: This variable represents the Maize yield. It is calculated using a Mitscherlich231 Baule production function (Schilling 2000). F
polynomic functions etc.). Data from Worldbank.

Mineralized_nutrients_from_SOM = SOM_Mineralization_rate*Nutrient_content_in_SOM

UNITS: ton/Ha/month

Month_to_year = 12

UNITS: month/year

Monthly_effect_factor_of_nitrogen_on_yield =

Effect_factor_of_nitrogen_on_yield*Month_to_year

UNITS: Ha*month/ton

Monthly_fertilizer_subsidies = (Annual_FISP/Month_to_year)*Share_of_FISP_to_SSF

UNITS: ton/month

monthly_Yield_plateau = Yield_plateau/Month_to_year

UNITS: ton/Ha/month

More_access_to_fertilizer_policy = Increased_input_from_FISP

UNITS: ton/month

Nutrient_content_in_SOM = 0.03

UNITS: dmnl

DOCUMENT: This constant variable represents the share of plant nutrients that are contained in soil organic matter (such as nitrogen, phosphorus, potassium, etc.).

Nutrient_uptake_from_fertilizer = Fertilizer_application_per_ha_Maize

UNITS: ton/Ha/month

DOCUMENT: This variable calculates the annual total nitrogen fertilizer application in tons.The amount of nitrogen coming from the fertilisers applied to the soil

Nutrients_from_Animals_manure = 0.025

UNITS: Ton/Ha/month

DOCUMENT: This variable represents organic nitrogen application on arable land through animal manure. Data from Gerber (2016)

Organic_matter_addition_from_intercrop_intervention = 0.023

UNITS: ton/Ha/month

DOCUMENT: This constant variable represents the amount of organic matter that is additionally worked into the soil under the organic matter addition intervention.Yearly organic matter addition= 0.28 ton /ha/year Monthly organic matter addition= 0.28/12= 0.023 ton /ha/month

Plant_Residues = Maize_yield*Share_of_plants_residues_remaining_on_the_field

UNITS: Ton/Ha/month

DOCUMENT: The amount of plant residues left above the ground.

Policy_option_three_switch = 0

UNITS: dmnl

Policy_switch_of_SOM_from_livestocks = 0

UNITS: dmnl

Policy_Switch_organic_matter_addition_2 = 0

UNITS: dmnl

DOCUMENT: This is a switch variable for the organic matter intervention. There is no organic matter addition if the switch has the value 0 and there is organic matter addition if the switch has the value 1.

Policy_switch_plant_residues_remaining = 0

UNITS: 1

Private_fertilizer_expenditure = share_of_fertilizer_expenditure*Households_free_cash_sector.Expenditure_on_others

UNITS: kwacha/ month

DOCUMENT: This variable represents the fertilizer expenditures spent by farmers.

Reduced_Fertilizer_from_FISP_with_PHL_policy = (Input_from_FISP-Hermetic_bag_Storage_Policy_sector.Available_fund_for_storage_bag)/Fertilizer_price

UNITS: ton/Months

Relative_soil_organic_matter = Soil_Organic_Matter/Initiall_soil_organic_matter

UNITS: dmnl

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

share_of_fertilizer_expenditure = 0.25

UNITS: dmnl

DOCUMENT: This constant variable represents the share of household expenditure used to purchase fertilizer.

Source: Mulenga, C. (2013). The State of Food Insecurity in Lusaka, Zambia. AFSUN Food Security Series, (19).

Share_of_FISP_to_SSF = 0.77

UNITS: dmnl

Share_of_plants_residues_remaining_on_the_field =
IF(Policy_switch_plant_residues_remaining=1) AND(TIME> 144) THEN
Increased_share_of_plants_residues_remaining_on_he_field ELSE 0.5
UNITS: dmnl
DOCUMENT: This constant represents the share of plant residues that actually remain on the field and are incorporated to the soil.
SOM_from_Livestocks = IF
(Policy_switch_of_SOM_from_livestocks=1)THEN"Livestock_(POULTRY)_policy_sector"."Livestock_(CHICKEN)"*SOM_from_per_livestocks/Maize_yeild_&_production_sector.Maize_harvested_area ELSE 0
UNITS: Ton/Ha/month
DOCUMENT: This constant represents the annual amount of organic matter applied through animal manure (per hectare arable land).
SOM_from_per_livestocks = 0.000183
UNITS: ton/chicken/month
SOM_Mineralization_TIME = 360
UNITS: months
Start_time_of_organic_matter_intervention = 144
UNITS: month
DOCUMENT: This constant defines the policy start time .
Total_Nutrient_uptake_by_Maize =
(Mineralized_nutrients_from_SOM+Nutrient_uptake_from_fertilizer)*Effect_of_SOM_on_nitrogen_uptake
UNITS: ton/Ha/month
DOCUMENT: This variable represents the total nitrogen uptake from fertilizer and nutrients content in SOM.
Yield_plateau = 9
UNITS: Ton/ha/year
DOCUMENT: This constant variable is part of the Mitscherlich-Baule production function representing the Maize yield under perfect factor availability.

Agriculture_land_sector:

Arable_land(t) = Arable_land(t - dt) + (Change_in_Arable_land_conversion_rate) * dt

INIT Arable_land = 2949000

UNITS: ha

DOCUMENT: This stock represents the value of arable land.In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land. Data estimated from FAOSTAT (2010)

INFLOWS:

Change_in_Arable_land_conversion_rate =

MIN(MIN(Desired_Arable_land/Arable_land_conversion_time,

Maximum_arable_land_demand/Arable_land_conversion_time)-

Arable_land/Arable_land_conversion_time,

Potential_arable_land/Arable_land_conversion_time)

UNITS: ha/Months

DOCUMENT: This variable represents the net change from potential arable land into arable land.Its main driver is arable land demand. Arable land conversion can be limited either by the absence of potential arable land (that could be converted), or by the limited endowment of the agricultural sector (that results in a maximal area which can be cultivated by the current agricultural workforce).

Potential_arable_land(t) = Potential_arable_land(t - dt) + (-

Change_in_Arable_land_conversion_rate) * dt

INIT Potential_arable_land = 7.05906e+07

UNITS: ha

DOCUMENT: This stock represents the level of potential arable land .Under the given population scenario, arable land is not a limiting factor, assuming that there is a situation of abundant potential arable land. Data from FAO (2010)

OUTFLOWS:

Change_in_Arable_land_conversion_rate =

MIN(MIN(Desired_Arable_land/Arable_land_conversion_time,

Maximum_arable_land_demand/Arable_land_conversion_time)-

Arable_land/Arable_land_conversion_time,
Potential_arable_land/Arable_land_conversion_time)
UNITS: ha/Months
DOCUMENT: This variable represents the net change from potential arable land into arable land.Its main driver is arable land demand. Arable land conversion can be limited either by the absence of potential arable land (that could be converted), or by the limited endowment of the agricultural sector (that results in a maximal area which can be cultivated by the current agricultural workforce).
Arable_land_conversion_time = 60
UNITS: month
DOCUMENT: This constant variable represents the time it takes to convert potential arable land into arable land.
Average_population_growth_rate =
TREND(Households_food_insecurity_sector.Total_Population, TIME_SPAN, Initial_population_growth)
UNITS: dmnl/month
DOCUMENT: This variable calculates the average annual past trend of population growth.
Desired_Arable_land =
Arable_land*(1+Households_free_cash_sector.Supply_demand_balance)+Arable_land*(1+Households_free_cash_sector.Supply_demand_balance)*Average_population_growth_rate*Switch_of_land_anticipation*Estimated_arable_land_conversion_time
UNITS: ha
DOCUMENT: This variable defines the demand for arable land by adjusting the current level to the food security status of the household population. If there is a food surplus, arable land demand decreases. And if there is food scarcity, arable land demand increases.
Estimated_arable_land_conversion_time = 48
UNITS: month
DOCUMENT: This constant variable represents the estimated time need to convert potential arable land into arable land and equals the actual value (arable land conversion time). It is used to anticipate land use change to the needs of the population.
Initial_population_growth = 1

UNITS: dmnl/month

DOCUMENT: This variable represents an estimate of the initial population growth rate trend. It is assumed to be 0 since the model starts in equilibrium condition (where population doesn't grow).

Initial_population_growth_1 = 0

UNITS: dmnl/month

Maximum_arable_land_demand = Share_of_agriculture_workforce*Households_food_insecurity_sector.Total_Population*Maximum_area_cultivate_per_agriculture_workforce

UNITS: ha

DOCUMENT: This variable represents the maximum area that can be cultivated given the current agricultural workforce and its productiveness.

Maximum_area_cultivate_per_agriculture_workforce = 0.6

UNITS: ha/person

DOCUMENT: This variable represents the maximum productiveness of an agricultural workforce in terms of area coverage. The value is around 0.6 hectares per person per year.Data from Gerber(2016)

Share_of_agriculture_workforce = 0.241753

UNITS: dmnl

DOCUMENT: This constant variable represents the share of people active in agriculture relative to the total population. The value was estimated from a data set from Zambia. (FAO, Food and Agriculture Organisation).

Switch_of_land_anticipation = 1

UNITS: dmnl

DOCUMENT: This is a switch variable for the land anticipation policy. There is no anticipation if the switch has the value 0 and there is anticipation if the switch has the value 1.

TIME_SPAN = 60

UNITS: month

DOCUMENT: This variable defines the time frame over which the past population growth rate is calculated.

Households_free_cash_sector:

Perceived_demand_supply_balance(t) = Perceived_demand_supply_balance(t - dt) + (Change_in_perceived_demand_supply_balance) * dt

INIT Perceived_demand_supply_balance = 0.6

UNITS: dmnl

DOCUMENT: This stock represents the perception of the ratio between supplied and demanded quantity of Maize.

(Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA)

INFLOWS:

Change_in_perceived_demand_supply_balance = (Supply_demand_balance-Perceived_demand_supply_balance)/Time_for_perceived_supply_demand_balance

UNITS: Per Month

DOCUMENT: This variable represents change of the perception of the ratio between Maize supplied and demanded quantity of Maize.

Small_scale_farmer_Households_free_cash(t) = Small_scale_farmer_Households_free_cash(t - dt) + (Income_from_Maize + Income_from_others_crop + Income_from_livestock - Expenditure_on_food_consumption - Expenditure_on_others) * dt

INIT Small_scale_farmer_Households_free_cash = 134000000

UNITS: kwacha

DOCUMENT: This stock represents the household free cash through Maize sales and others major crops sale produced by small scale farmer.

INFLOWS:

Income_from_Maize = Households_cash_from_Maize_sales

UNITS: kwacha/ month

Income_from_others_crop = Others_crop_income

UNITS: kwacha/ month

DOCUMENT: This is the flow of household income from other crops.

Income_from_livestock = IF(Switch_of_livestock_policy=1) AND (TIME >144) THEN "Livestock_(POULTRY)_policy_sector".Gross_margin_from_livestock ELSE 0

UNITS: kwacha/ month

OUTFLOWS:

Expenditure_on_food_consumption = ((Small_scale_farmer_Households_free_cash*Share_of_household_expenditure_on_food)/Food_coverage_time)*Share_of_purchase_cereals

UNITS: kwacha/ month

DOCUMENT: This variable represents the expenditure that farmers spend to buy food items.

Expenditure_on_others = (Share_of_others_expenditure*Small_scale_farmer_Households_free_cash)/Others_expenditure_coverage_time

UNITS: kwacha/ month

Average_bean_price = 6000

UNITS: kwacha/Ton

Average_Cassava_harvest_area = GRAPH(TIME)

(1.0, 198692.0), (45.875, 196032.0), (90.75, 190427.0), (135.625, 191359.0), (180.5, 158390.0), (225.375, 165359.0), (270.25, 177655.0), (315.125, 186814.0), (360.0, 184876.0)

UNITS: ha

DOCUMENT:

Data from FAOSTAT (2010-2018)

Average_cassava_price = 3656

UNITS: kwacha/ton

DOCUMENT: Data from FAOSTAT

Average_groundnuts_harvest_area = GRAPH(TIME)

(1.0, 254566.0), (45.875, 209237.0), (90.75, 176162.0), (135.625, 207249.0), (180.5, 237423.0), (225.375, 228880.0), (270.25, 237464.0), (315.125, 262612.0), (360.0, 259479.0)

DOCUMENT: Data from FAOSTAT (2010-2018)

Households_food_insecurity_sector:

Maize_available_for_household_consumption(t) =

Maize_available_for_household_consumption(t - dt) + (Maize_Purchased +

Maize_storage_rate_for_self_conumption - Monthly_Maize_consumption) * dt

INIT Maize_available_for_household_consumption = 736000

UNITS: Ton

DOCUMENT: This stock represents the availability of food for household consumption. That accumulates the Maize storage rate and Maize purchase rate, and the initial value is calculated based on the assumption.

INFLOWS:

Maize_Purchased = Maize_purchase_ability/Households_free_cash_sector.Maize_price_per_ton

UNITS: ton/month

DOCUMENT: This variable represents the monthly amount of Maize being purchased from the market for consumption.

Maize_storage_rate_for_self_conumption = Maize_storage/Maize_storage_time

UNITS: ton/month

OUTFLOWS:

Monthly_Maize_consumption = MIN(Maximum_Maize_available_for_consumption,

Food_demand_covered_with_Maize_in_small_scale_farmer_households)

UNITS: Ton/month

DOCUMENT: This variable represents the monthly household Maize consumption .

Maize_storage(t) = Maize_storage(t - dt) + (Maize_production -

Maize_storage_rate_for_self_conumption - Maize_sale - Post_harvest_loss) * dt

INIT Maize_storage = 382000

UNITS: Ton

DOCUMENT: This Maize storage stock is the accumulation of all small scale farmer Maize production harvested in a given year. And this stock diminishing by Maize sales and post-harvest loss outflows.The initial value was calculated based on the assumption by deducting post-harvest loss and Maize sales from Maize production.

INFLOWS:

Maize_production = Maize_yeild_&_production_sector.Seasonal_Maize_production

UNITS: ton/month

OUTFLOWS:

Maize_storage_rate_for_self_conumption = Maize_storage/Maize_storage_time

UNITS: ton/month

Maize_sale = (Maize_storage*Share_of_Maize_sold)/Maximum_Maize_sold_time

UNITS: ton/month

DOCUMENT: This variable represents the monthly amount of Maize being sold at a market. In the case of Zambia, Maize is partly sold and partly self-consumed, and this variable is only a share of the total production.

Post_harvest_loss = (Maize_storage*share_of_post_harvest_Maize_loss)/Maize_PHL_time

UNITS: ton/month

DOCUMENT: This variable represents the monthly amount of Maize being lost due to storage capacity.

Population_scenario(t) = Population_scenario(t - dt) + (Change_in_Population_Growth) * dt

INIT Population_scenario = 13605984

UNITS: people

DOCUMENT: This variable is used to generate the (exogenous) population growth pattern and therefore cannot be considered as a model variable.This variable represents the total population. Total population is an exogenous input

to the model .Total population in 2010 = 13605984 that is consider as a initial number of population in this model. Data from worldbank indicators.

INFLOWS:

Change_in_Population_Growth =

(Population_scenario*Average_population_growth_rate)/Month_per_year

UNITS: People/Months

Average_population_growth_rate = 0.0286

UNITS: dmnl/year

DOCUMENT: This variable represents average population growth rate from the last 10 years (2010-2018) .This variable is used to generate the (exogenous) population growth pattern and therefore cannot be considered as a model variable.Data from Worldbank.

Days_per_month = 30

UNITS: Days/month

DOCUMENT: This variable represents the number of days per month (30).

Desired_kcal_requirement_from_Maize =

(Per_capita_kcal_requirement_from_Maize*Days_per_month)*"Small-

_scale_farmer_population"

UNITS: Kcal/Months

DOCUMENT: This variable represents the monthly kcal requirement from Maize for smal scale farmers.

Desired_Maize_purchase =

MAX(Food_demand_covered_with_Maize_in_small_scale_farmer_households-

Monthly_Maize_consumption, 0)

UNITS: Ton/month

DOCUMENT: This variable represents the desired amount of Maize purchased to fill up the gap between food demand and availability for consumption.

Desired_Maize_spend =

Households_free_cash_sector.Maize_price_per_ton*Desired_Maize_purchase

UNITS: kwacha/month

DOCUMENT: This variable represents the amount of money required to purchase Maize to fulfill the farmer's food demand.

Desired_Maize_storage = Maize_storage*Share_of_post_harvest_loss_data+Maize_storage

UNITS: Ton

DOCUMENT: This policy variable represents the desired Maize storage by adding the share of Maize lost due to inadequate storage capacity.

Desired_nourished_population = "Small-_scale_farmer_population"

UNITS: people

desired_share_of_Maize_storage = (Desired_Maize_storage-Maize_storage)/Maize_storage

UNITS: dmnl

DOCUMENT: This policy variable represents the desired share of Maize need to be storage to reach the goal of zero post-harvest loss.

Desired_share_of_post_harvest_loss = Share_of_post_harvest_loss_data-

desired_share_of_Maize_storage

UNITS: dmnl

DOCUMENT: This policy variable represents the desired share of post-harvest loss to reach the goal of zero post-harvest loss.

Equilibrium_population = 13605984

UNITS: people

DOCUMENT: This constant variable represents the equilibrium population, that equals the initial population.

"Food_deficit_(kcal_per_person_per_day)" = Monthly_food_deficit/Days_per_month/"Small-_scale_farmer_population"

UNITS: kcal/person /day

DOCUMENT: This variable represents the number of calories needed to lift the undernourished from the household population.

Food_demand_covered_with_Maize_in_small_scale_farmer_households = (Desired_kcal_requirement_from_Maize/kcal_per_kg_Maize)/kg_per_ton

UNITS: Ton/month

DOCUMENT: This variable represents the monthly Maize demand for small scale farmer households. Here, Maize demand depends on the small scale farmer household population's requirement.

Kcal_consumption_from_Maize = (kg_per_ton*Monthly_Maize_consumption*kcal_per_kg_Maize)

UNITS: Kcal/Months

DOCUMENT: This variable represents the number of kilocalories from Maize products that are consumed per person per month. It is a key indicator for measuring the food security.

kcal_per_kg_Maize = 3071

UNITS: kcal/kilograms

DOCUMENT: This variable represents the number of kilo calories per kilogram Maize. It is estimated from FAO data.

kg_per_ton = 1000

UNITS: kilogram/ton

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

Maize_PHL_time = 12

UNITS: month

Maize_purchase_ability =

MIN(Households_free_cash_sector.Expenditure_on_food_consumption*share_of_household_expenditure_on_purchase_Maize, Desired_Maize_spend)

UNITS: kwacha/ month

DOCUMENT: This variable represents the ability to purchase Maize from market .

Maize_storage_time = 12

UNITS: month

Maximum_Maize_available_for_consumption =

(Maize_available_for_household_consumption/Maximum_Maize_coverage_time)

UNITS: Ton/month

DOCUMENT: This variable represents the maximum available food for household consumption for one month.

Maximum_Maize_coverage_time = 12

UNITS: month

DOCUMENT: Minimum time household's reserves of Maize are expected to last (5 weeks)(Fuentes, 2002).

5 weeks=35 days

35/30=1.17 month

Maximum_Maize_sold_time = 12

UNITS: month

Month_per_year = 12

UNITS: month/year

DOCUMENT: This variable represents the number of month per year (12).

Monthly_food_deficit = (Desired_kcal_requirement_from_Maize-Kcal_consumption_from_Maize)*Population_undernourished/"Small-_scale_farmer_population"

UNITS: Kcal/Months

Per_capita_kcal_requirement_from_Maize =

Share_of_kcal_from_Maize*Per_capita_kcal_reuirement

UNITS: kcal/person/day

Per_capita_kcal_reuirement = 2200

UNITS: kcal/person/day

DOCUMENT: This variable represents the per capita kilocalorie requirement. 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)

Policy_1_starting_time = 144

UNITS: months

Policy_switch_for_post_harvest_loss_reduction = 0

UNITS: dmnl

Population_nourished = (Kcal_consumption_from_Maize/Desired_kcal_requirement_from_Maize)*"Small-_scale_farmer_population"

UNITS: person

DOCUMENT: This variable represents the nourished farmer population are those people whose food intake equals the minimum level of daily kcal requirements.

Population_undernourished = Desired_nourished_population-Population_nourished

UNITS: person

DOCUMENT: This variable represents the nourished farmer population are those people whose food intake falls below the minimum level of daily kcal requirements.

Prevalence_of_undernourishment = (Desired_nourished_population-Population_nourished)/Desired_nourished_population

UNITS: 1

DOCUMENT: This variable represents the (PoU) at household level in this model that is indicator used to understand access to food in terms of dietary energy inadequacy.

share_of_household_expenditure_on_purchase_Maize = 0.25

UNITS: dmnl

DOCUMENT: This constant variable defines the share of food expenditure that is used to Maize. Source: Mulenga, C. (2013). The State of Food Insecurity in Lusaka, Zambia. AFSUN Food Security Series, (19).

Share_of_kcal_from_Maize = 0.60

UNITS: dmnl

DOCUMENT: 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%).This variable represents the past share of kilocalories coming from Maize compared
to the total diet. The past trajectory was calculated from FAO, and the last value is applied as future scenario. Data calculated from FAO.

Share_of_Maize_sold = 0.52

UNITS: DMNL

DOCUMENT: In a small scale farming system that partly focuses on self-consumption, only parts of the production are sold at a market. This constant variables defines the share of Maize that is sold from the farmers own production.

Source: .HarvestPlus Research for action (NO.5) September 2015.Maize Consumption Patterns and Consumer Preferences in Zambia (Hugo De Groote1*, Zachary Gitonga1, Earnest Kasuta2, Dorene Asare-Marfo3, and Ekin Birol)

Share_of_PHL_after_policy_implementation = Desired_share_of_post_harvest_loss*Hermetic_bag_Storage_Policy_sector.Effect_of_Hermetic_storage_bag_implementation_policy_on_PHL

UNITS: dmnl

DOCUMENT: This variable represents the share of PHL after implementing the policy.

Share_of_post_harvest_loss_data = 0.40

UNITS: dmnl

DOCUMENT: This constant variables defines the share of Maize that is lost due poor storage capacity. Data from (FAO, 2011; Hodges et al., 2011; Deloitte, 2015)

share_of_post_harvest_Maize_loss = IF(Policy_switch_for_post_harvest_loss_reduction=1) AND (TIME >Policy_1_starting_time) THEN Share_of_PHL_after_policy_implementation ELSE Share_of_post_harvest_loss_data

UNITS: dmnl

"Share_of_small-_scale_farmer_household_population" = 0.5237

UNITS: dmnl

DOCUMENT: This constant value represents the share of small scale household population among total population in Zambia. It is estimated from 2015 living conditions monitoring survey (LCMS) report of Zambia.

"Small-_scale_farmer_population" = Total_Population*"Share_of_small-_scale_farmer_household_population"

UNITS: people

DOCUMENT: This variable represents the total small scale farmer households population in Zambia.

Switch_population = 1

UNITS: dmnl

DOCUMENT: This is a switch variable for the population scenario.If the variable takes on the value 0, a constant population is applied. If the variable takes on the value 1, the exogenous population growth scenario is applied.

Total_Population = Equilibrium_population*(1-Switch_population)+Population_scenario*Switch_population

UNITS: people

DOCUMENT: This variable represents the countries total population and builds the main exogenous scenario driving the model.

Hermetic_bag_Storage_Policy_sector:

NPV_Of_Maize'_STORAGE_COST(t) = NPV_Of_Maize'_STORAGE_COST(t - dt) + (Change_of_NPV_Maize_STORAGE_COST) * dt

INIT NPV_Of_Maize'_STORAGE_COST = 0

UNITS: kwacha

DOCUMENT: Net present value is a financial model that calculates the net value of a project today by discounting future cash flows over the lifetime of a project by an opportunity cost of capital. This stock calculated the future return on this policy investment.

INFLOWS:

Change_of_NPV_Maize_STORAGE_COST =
IF(TIME>Policy_start_time)THEN(Total_hermetic_bag_cost/Discount_factor)ELSE(0)
UNITS: kwacha/month
NPV_of_PHML_reduction(t) = NPV_of_PHML_reduction(t - dt) +
(Change_of_NPV_Post_harvest_Maize_production_loss) * dt
INIT NPV_of_PHML_reduction = 0
UNITS: ton
INFLOWS:
Change_of_NPV_Post_harvest_Maize_production_loss =
IF(Households_food_insecurity_sector.Policy_switch_for_post_harvest_loss_reduction=1)
AND(TIME>132) THEN
(Households_food_insecurity_sector.Desired_Maize_storage/Time_to_adjust_cost) ELSE 0
UNITS: ton/month
Available_fund_for_storage_bag =
(Share_of_fund_for_Hermetic_storage_bag_purchase*Monthly_input_from_FISP)
UNITS: kwacha/ month
Cost_per_bag = 40.56
UNITS: kwacha/bag
Cost_per_ton_Maize_loss_reduction =
IF(NPV_of_PHML_reduction>0)THEN(NPV_Of_Maize'_STORAGE_COST/NPV_of_PHML_
reduction)ELSE(0)
UNITS: Kwacha/Ton
Desired_fund_for_storage_bag = (Cost_per_bag*Desired_Hermetic_storage_bag)
UNITS: kwacha/ month
Desired_Hermetic_storage_bag =
(Desired_monthly_Maize_storage/Hermetic_storage_bag_capacity)
UNITS: bag/Months
Desired_Maize_storage = Households_food_insecurity_sector.Desired_Maize_storage
UNITS: Ton
Desired_monthly_Maize_storage = Desired_Maize_storage/storage_adjustment_time
UNITS: ton/Months

Discount_factor = (((1+Monthly_discount_rate)/(1+Reference_discount_rate))^Time_period)

UNITS: unitless

Discount_rate = 0.09

UNITS: Per year

DOCUMENT: This constant variable represents the interest rate used to determine the present value of future cash flows of policy implementation.

Source: Zambia central bank

Effect_of_Hermetic_storage_bag_implementation_policy_on_PHL = Maize_storage/Desired_monthly_Maize_storage

UNITS: dmnl

Hermetic_storage_bag_capacity = 0.1

UNITS: ton/bag

Maize_storage = Storage_bag_order_rate*Hermetic_storage_bag_capacity

UNITS: Ton/month

Month_to_year = 12

UNITS: month/year

Monthly_discount_rate = Discount_rate/Month_to_year

UNITS: Per Month

Monthly_input_from_FISP = Soil_organic_matter_sector.Input_from_FISP

UNITS: kwacha/ month

Net_profit_per_ton_Maize_from_storage_policy = IF (Households_food_insecurity_sector.Policy_switch_for_post_harvest_loss_reduction=1) AND (TIME >144) THEN (Households_free_cash_sector.Maize_price_per_ton-Cost_per_ton_Maize_loss_reduction) ELSE 0

UNITS: kwacha/ton

DOCUMENT: This variable represents the net profit from per ton Maize storage.

Policy_start_time = 144

UNITS: Months

Reference_discount_rate = 0

UNITS: Per Month

Share_of_fund_for_Hermetic_storage_bag_purchase =
Desired_fund_for_storage_bag/(Monthly_input_from_FISP)
UNITS: 1
storage_adjustment_time = 12
UNITS: month
Storage_bag_order_rate = Available_fund_for_storage_bag/Cost_per_bag
UNITS: bag/Months
Time_period = (TIME-Policy_start_time)/Time_units
UNITS: unitless
Time_to_adjust_cost = 12
UNITS: month
Time_units = 360
UNITS: month
Total_hermetic_bag_cost = Available_fund_for_storage_bag
UNITS: kwacha/month

"Livestock_(POULTRY)_policy_sector":
"Livestock_(CHICKEN)"(t) = "Livestock_(CHICKEN)"(t - dt) + (Livestock_input - LIVESTOCK_SOLD - livestock_death) * dt
INIT "Livestock_(CHICKEN)" = 0
UNITS: chicken
DOCUMENT: The amount of chicken held by all the Maize farmers in the community. This amount does not include the livestock held by no farmers.
INFLOWS:
Livestock_input = IF(Households_free_cash_sector.Switch_of_livestock_policy=1) AND(TIME>144) THEN Initial_Livestock_purchase ELSE 0
UNITS: chicken/Months
DOCUMENT: The amount of chicken added to the stock every year.
OUTFLOWS:
LIVESTOCK_SOLD = "Livestock_(CHICKEN)"/Average_time_for_livestock_sold
UNITS: chicken/Months

DOCUMENT: The amount of poultry sold. While some chickens are sold as soon, they reach the proper size; others are kept for longer periods and used for producing eggs. The amount of chicken sold per year is calculated as the number of chickens divided by the average time the livestock is kept.

livestock_death = ("Livestock_(CHICKEN)"*Death_rate)/Month_to_year

UNITS: chicken/Months

DOCUMENT: The amount of chicken dying every year.

Average_time_for_livestock_sold = 24

UNITS: month

Chicken_price = 35

UNITS: kwacha/chicken

DOCUMENT: Source: Poultry Association of Zambia

Death_rate = 0.15

UNITS: dmnl/year

Egg_price = 0.5

UNITS: kwacha/egg

Egg_production_from_chicken = ("Livestock_(CHICKEN)"*Egg_production_per_chicken)/Month_to_year

UNITS: egg/month

DOCUMENT: The total amount of eggs produced.

Egg_production_per_chicken = 180

UNITS: egg/chicken/year

DOCUMENT: http://www.fao.org/3/Y4628E/y4628e03.ht

A good hen of most breeds is expected to lay about 300 eggs in a 12 month laying period and about 340 in a 14 month period (LSCS 2007).

Gross_margin_from_livestock = Total_income_from_chicken_&_egg_sold-Livestock_maintenance_cost

UNITS: kwacha/ month

Income_from_chicken_sold = Chicken_price*LIVESTOCK_SOLD

UNITS: kwacha/month

DOCUMENT: The total amount of revenue produced from eggs’ sales

Income_from_egg = Egg_production_from_chicken*Egg_price

UNITS: kwacha/month

Initial_Livestock_purchase =

Soil_organic_matter_sector.Private_fertilizer_expenditure/Chicken_price

UNITS: chicken/Months

Livestock_maintenance_cost =

"Livestock_(CHICKEN)"*Monthly_unitary_livestock_maintenance_cost

UNITS: kwacha/ month

DOCUMENT: The cost associated with keeping the chickens.

Month_to_year = 12

UNITS: month/year

Monthly_unitary_livestock_maintenance_cost = 2.81

UNITS: kwacha/chicken/ month

Total_income_from_chicken_&_egg_sold = Income_from_chicken_sold+Income_from_egg

UNITS: kwacha/month