



The Maize Value Chain in Zambia: Dynamics and Resilience Towards Production Shocks

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Abstract

Zambia is a country whose food security largely depends on maize. In the light of expected structural maize deficits and the likely occurrence of shock events, the aim of this thesis is to test the resilience of the Zambian maize value chain towards production shocks in terms of food supply security, and to find policy recommendations on how to increase this resilience. To that end, I devised and applied a new framework for measuring resilience properties using System Dynamics, which relies on comparing the development of food security indicators between the base run and the respective shock scenario run of a simulation model. Results show that the value chain is quite resilient towards floods and exchange rate shocks, moderately vulnerable towards changes in fertilizer subsidy programmes, and very vulnerable towards droughts, especially prolonged ones. In general, the resilience of the value chain towards one-time shocks is good due to the existence of maize buffer stocks that people can consume when production is low. However, the value chain is not very resilient if faced with two or more different shocks, as buffer stocks are quickly depleted and maize demand cannot be serviced any more. The resilience properties are also strongly affected by demand adjustments of consumers in response to changing maize availability, and moderately affected by the distribution of maize in between the informal and formal value chain and the storage policies of FRA. The observed resilience properties can endogenously be improved using smart long-term maize storage policies that exploit surplus production years.

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List of Abbreviations

AT	Adjustment Time
ADER	Average Dietary Energy Requirements
ADESA	Average Dietary Energy Supply Adequacy
ADESM	Adjusted Dietary Energy Supply with Maize
CFS	Crop Forecast Survey
CT	Coverage Time
DAR	Desired Acquisition Rate
DES	Dietary Energy Supply
FAO	Food and Agriculture Organization of the United Nations
FRA	Food Reserve Agency
FOM	Figure-of-Merit
FSRP	Food Security Research Project (at the Michigan State University)
FSP	Fertilizer Subsidy Programme
IAPRI	Indaba Agricultural Research Institute
PoU	Prevalence of Undernourishment
WFP	World Food Programme
WHO	World Health Organization

1. Introduction

1.1 Problem Description

Zambia is a society built on maize. Since the colonial period, a large part of the government's legitimacy has depended on its ability to fulfil the implicit social contract with its constituency that requires it to ensure a sufficient maize supply for the population (Jayne & Jones, 1997). And the importance of maize has not waned over the last decades: even today, maize still accounts for over 50% of the calories consumed by an average Zambian citizen (FAO, 2015b), whereby especially the poorest strata of society depend on maize over-proportionally (Nicole Mason & Jayne, 2009). This might not be a problem per se as would Zambians live in a state of food security – but unfortunately, the opposite is true. FAO's (2014b) food security indicators show that Zambia has only been able to supply around 90% of the calories its citizens need to live a healthy and active life over the last years; and Gerber (2015) expects a structural maize deficit to emerge in Zambia in the near future. On top of this generally tense situation, weak political and economic institutions, bad infrastructure, heavy reliance on one main staple food crop and high exposition to sudden and strong changes in its climatic, political and economic environment leave Zambia in a position of high vulnerability on many levels (Bertelsmann Transformation Index, 2012; Stockholm Resilience Centre, 2012; UNDP, 2014).

Given the central role of maize in Zambia, the population's access to maize can legitimately be seen as a proxy for overall food security in Zambia. My thesis will thus explore what happens to the maize supply in Zambia when it is faced with production shocks. I want to find out how resilient the mechanisms that bring the maize “from farm to fork”, i.e. the maize value chain, are towards production shocks – and what can be done within the political and economic boundaries of Zambia to enhance those resilience properties. To that end, I will devise a framework that enables the quantitative measurement of resilience

with a System Dynamics (SD) simulation model. The completion of this case study will also serve as a test of the usefulness and feasibility of my resilience framework.

1.2 Research Questions and Objectives

To substantiate the goals for this thesis, I will break them down into research questions and research objectives. My central research question is:

What are the resilience properties of the maize value chain in Zambia towards production shocks in terms of ensuring sufficient maize supply, and how can the resilience be improved endogenously?

“Sufficient” in this context means enough supply to meet the population’s demand for maize, and thereby ensuring food security.

Resilience will be measured in terms of the integral between the base run and the respective shock scenario runs for an indicator that I call the “Adjusted Dietary Energy Supply with Maize” (ADESM). This parameter will serve as a proxy for food security and is based on a food security indicator by FAO (2014) called “Average Dietary Energy Supply Adequacy” (ADESA), which measures the supply of maize in relation to demand. I will discuss these indicators and their relation to food security in greater detail in chapter 2.

To be more concise about what I am trying to achieve in this thesis, it is useful to split my research question into a set of **sub-questions**. These are:

1. What is the physical and economic structure of the maize value chain in Zambia?
2. According to which rules and decisions does the maize move through the value chain?
3. What are the most relevant and likely production shocks that may hit the maize value chain in Zambia and how can their effects be represented in the model?
4. How do these shocks affect the ADESM through the value chain, i.e. how resilient is the value chain to production shocks in terms of maize supply security?

5. What policies can endogenously, i.e. within the political, geographical and economic boundaries of Zambia, improve the resilience of the value chain towards production shocks?

According to Saunders & Lewis (2012: chapter 1), it helps to increase the clarity and focus of a research project to translate the research questions into tangible **research objectives**.

For my thesis, these are:

1. To devise an operational framework for measuring resilience in a quantified SD model
2. To define a clear and measurable indicator that serves as a proxy for food security in the context of maize supply in Zambia
3. To create a valid quantitative System Dynamics model of the maize value chain in Zambia
4. To select the most relevant production shocks that may affect the maize value chain in Zambia in terms of creating food supply insecurity, and find a way to represent these shocks' effects in the model
5. To assess how resilient the maize value chain in Zambia is towards these shocks in terms of my resilience framework
6. To devise policy recommendations that can endogenously, i.e. within the political, geographical and economic boundaries of Zambia, improve the resilience of the value chain towards production shocks

1.3 Research Methodology

Having established the goals of my study in the form of research questions and research objectives, I will explicate the way in which I intend to fulfil them in the following section.

1.3.1 Research Design

My research strategy is best characterized as a case study using quantitative System Dynamics modelling. Saunders & Lewis (2012: p.116) define a **case study** as a “*research strategy, which involves the investigation of a particular contemporary topic within its real-life context, using multiple sources of evidence*”. This describes exactly what I am trying to accomplish: using a variety of sources to examine the structure of the particular case and explain its behaviour. As such, I want to answer the questions “how” is the case structured and “why” does it behave the way it does. The study will be *longitudinal*, as I am interested in exploring how the resilience properties of the value chain develop over time in the case of a shock or a series of consecutive shocks.

The case study is carried out using a **quantitative System Dynamics modelling and simulation** approach. The great advantage of formal modelling with SD in terms of helping to answer the research question is that it forces the modeller to thoroughly think through every causal connection, creating a deep understanding and giving feedback in terms of model behaviour when there are weak points in one’s dynamic hypothesis. Using a simulation model furthermore enables me to quantitatively measure the impact of different scenarios on my resilience indicators – a necessary prerequisite to answering my central research question. Moreover, modelling with System Dynamics has proven to be a very useful tool for analysing value chains in many instances (Angerhofer & Angelides, 2000).

My thesis will thereby largely follow the well-established framework for System Dynamics modelling projects by Sterman (2000: chapter 3), that proposes the following schema:

1	Problem articulation
2	Model conceptualization
3	Formulation of simulation model
4	Model testing and validation

5	Analysis and evaluation
6	Policy design

Table 1: System Dynamics modelling process template

Luna-Reyes & Andersen (2003: p. 275) show that similar frameworks have been recommended and used by a several prominent System Dynamics practitioners.

My thesis will encompass *exploratory*, *descriptive* and *explanatory* elements (Saunders & Lewis, 2012: ch. 5). The *exploratory* part will be to clarify the nature of the problem, i.e. gathering information about the structure and behaviour of the value chain and finding out which are likely and relevant shocks that may affect the value chain. This leads to the *descriptive* part, which consists of describing the value chain, or to be more precise, my dynamic hypothesis about how it is structured and behaves, in the form of a quantified SD model. Finally, in the *explanatory* part, I will use the simulation results to formulate hypotheses about the structural causes of the resilience properties observed and derive policy recommendations from that.

1.3.2 Data Collection and Analysis

Since I did not have the opportunity to go to Zambia myself for first-hand data collection, my thesis is based on secondary data, academic literature and expert interviews. To sample the secondary data and literature, I relied on **purposive sampling** (Saunders & Lewis, 2012, p. 138-139). Specifically, I tried to use critical and heterogeneous sampling in order to base my research on secondary data and literature that is relevant and diverse: this means that I built my model using a multitude of sources, especially in cases where single sources seemed to be not that reliable. A good example for this is the time series data on maize production, trade and sales in Zambia: I collected this data in a lengthy process from a variety of different databases and research papers, cross-checking if the numbers fit together in a sensible way, discarding data that did not fit the other sources, looking for new data etc. (cf. appendix C1). The application of such data triangulation was also a way to increase the reliability of my research.

For the quantitative data that I needed to build the model, I mainly relied on databases of public institutions like the FAO, the World Bank and the Central Statistical Office of Zambia. Furthermore, I used time series data from tables and appendices of various research papers, most notably publications by the Indaba Agricultural Policy Research Institute (IAPRI) and its predecessor, the Food Security Research Project (FSRP) at the Michigan State University. In cases where necessary numerical data was not available in any of these sources, I relied on expert estimates from P. Nyanga (see below) for the remaining parameter values.

The qualitative data necessary to establish the context of my research and to conceptualize the model was taken from academic literature, reports of political organizations such as USAID or UN organizations. Here again, research papers by IAPRI and the FSRP were most helpful due to their high degree of detail. However, even these papers did not cover some of the micro-data that I needed to build the information feedback structure of my model.

Luckily, we were so fortunate to have Dr Progress Nyanga from the University of Zambia with us in Bergen for several weeks. Not only was he involved in many research projects about agriculture and rural development in Zambia, but also is he an active maize farmer, which qualifies him as one of the leading experts for the dynamics of the maize marketing sector in Zambia. I used two semi-structured interviews to collect data for the missing links in my research, where the first interview was more exploratory in nature, while the second one resembled more a disconfirmatory interview to increase confidence in the model's structure (Andersen et al., 2012). The interviews are reported in appendix D.

The way I went about the data analysis, i.e. the translation of numerical and qualitative data into my model, is described in extensive detail in chapter 4 and the comments for each variable in appendix A. In order to keep the introduction as concise as possible, I will therefore not repeat this content in detail here.

Reliability was ensured through the sampling and triangulation processes explained above and illustrated in further detail in chapter 4 and appendix C; while validity was warranted using a set of validation tests following Barlas (1996) that are described in chapter 6.

1.4 Relevance of the Topic

The relevance of the research stems from several considerations. On the one hand, there is the tense situation in Zambia concerning food security, the strong reliance on maize as a staple food crop and the high exposure to shocks that make the investigation of the resilience of the maize value chain a worthwhile undertaking. The food security situation in Zambia was touched upon in section 1.1 and I will explain it in greater detail in chapter 2.1, whereas the exposure to shocks will be discussed in detail in chapter 3.3.

While the value chain is central to understanding food security, as it represents the mechanism that actually get the food “from farm to fork”, most of the academic literature on food security focuses on the production or consumption level (Stave & Kopainsky, forthcoming), leaving the intermediate stages as a little understood “black box”. My thesis thus aims to fill this gap in the research and thereby create a more holistic understanding of the food security situation in Zambia.

Furthermore, there is the methodological argument that already quite a lot of conceptual literature, but few applications exist in resilience research, and many authors thus argue that conducting more comprehensive case studies to explore the usefulness and applicability of the concept is the necessary next step in resilience research (Janssen & Anderies, 2013).

1.5 Outline of the Thesis

Chapter 2 will discuss the problem background and context in greater detail, exploring the food security situation and specifics of the maize sector in Zambia, thereby further establishing the relevance of the topic. Together with chapter 3, it will constitute the literature review, placing my thesis in the context of other topical or methodological work

related to my research. Chapter 3 will establish the methodological framework and the metrics I will use to measure resilience.

Chapter 4 contains the description of my dynamic hypothesis in the form of the simulation model. Therein, I will develop the structure step by step and link it to the literature. Chapter 5 then discusses the behaviour of the model and the assumptions made concerning the inputs for the scenario analysis, so that the reader gains the necessary understanding of the dynamics to comprehend the results of the ensuing resilience analysis. Chapter 6 then examines the validity of the model by applying a series of well-established validation tests for quantitative SD models. The last step before the resilience properties can be tested is to choose and operationalize the shocks that I will expose the model to, which will be done in chapter 7.¹

Having laid all the groundwork in these first seven chapters, chapter 8 then presents and discusses the results of the resilience analysis. The model is subjected to 22 different production shock scenarios and its response in terms of the resilience framework is analysed, allowing us to answer research question 4. It will be shown that the value chain is quite resilient towards floods and exchange rate shocks, moderately vulnerable towards changes in fertilizer subsidy programmes, and very vulnerable towards droughts, especially prolonged ones. In general, the resilience of the value chain towards one-time shocks is good due to the existence of buffer stocks that can compensate for losses in production; whereas the resilience towards two or more shocks is low and the ADESM quickly breaks down. Furthermore, I will show that consumption adjustments in response to changes in maize availability and the distribution of maize between the formal and informal value chain have a significant impact on the resilience of the value chain towards a given shock.

¹ Even though chapter 7 is conceptually more a part of the “problem articulation” stage, I put it behind the model discussion chapters because the choice and operationalization of shocks depends on the model structure and the reader will thus be able to grasp the logic better having been exposed to the model already.

Based on these results, I will discuss possible policies to endogenously improve the resilience properties in chapter 9. I will show that a smart storage policy over the time horizon of several years, exploiting the occasionally occurring surplus harvest can significantly enhance the resilience towards production shocks. Chapter 10 then concludes the thesis by answering the research question, discussing limitations and indicating areas of further research.

2. Problem Background

As promised in the introduction, I will examine the relevance of my topic in more detail in this chapter. There are four main questions on which this relevance depends:

- How much of a problem is food insecurity in Zambia?
- How important is the role of maize for ensuring food security in Zambia?
- What is the role of the value chain in ensuring maize supply for the population?
- How susceptible is the maize sector in Zambia to shocks?

While the susceptibility to shocks will be discussed in chapter 3, I will explore the state of food security in Zambia and the role of maize in general, and the value chain in particular, in the following chapter.

2.1 Food Security in Zambia

To be able to evaluate the food security situation in Zambia, we must first develop an understanding of what food security actually means and how it can be measured. The 1996 World Food Summit defined food security as the state *“when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life”* (FAO, 2008: p.

1). According to FAO, IFAD, & WFP (2014), this state can be measured along the following four dimensions:

Availability	The quantity of (certain types of) food or nutrients that can be supplied in relation to the number of people in a given area
Access	The extent to which people actually have physical and economic access to the food available
Utilization	Gauging the ability of individuals to utilize the supplied food in a proper way, including an appropriate preparation of food and mix of nutrients
Stability	Assessing how stable the other three dimensions are over time

Table 2: Dimensions of food security

FAO (et al., 2014) currently uses a set of as much as 31 diverse indicators to measure these four dimensions and thus determine the state of food security. However, I neither have the room to discuss all of these indicators here, nor is it necessary. To get an understanding of the food security situation in Zambia, it suffices to look at a few central indicators from FAO (2014), which I summarized in table 3:

Indicator name	Short name	Description
Dietary Energy Supply	DES	Amount of food than can be supplied in a given area per person in the corresponding population
Average Dietary Energy Supply Adequacy	ADESA	Ratio comparing the DES with the ADER, showing if there is enough food for everyone assuming an even distribution of food among the population
Prevalence of Undernourishment	PoU	Probability that a randomly selected individual from the reference population consumes less than her calorie requirement for an active, healthy life
Average Dietary Energy Requirement	ADER	The amount of calories an individual needs on average to ensure it does not hunger, given medium physical activity and considering the specifics of the population and its environment

Table 3: Central indicators of food security

Equipped with this knowledge, we can now assess the situation of food security in Zambia by looking at the indicators. The Prevalence of Undernourishment, was as high as 48.3% for the last measurement period of 2012-13 (FAO, 2014). This means that every second Zambian you would meet by chance is undernourished – a clear sign that food security is still a big issue in Zambia.

But in how far is this lack of food security attributable to availability problems? Looking at the ADESA, we see that it has been fluctuating around 90% in the last years, meaning Zambia could only supply 90% of the calories that its citizens need for a healthy lifestyle. Moreover, Gerber (2015) expects that Zambia will enter a structural maize deficit in the near future due to stagnating harvests and growing population, making the supply situation even worse than it has been in the relatively good last harvest years.

Hence, we can conclude that food insecurity is an on-going problem in Zambia, that not only stems from an inefficient distribution of food in the society (*access* dimension), but also from the fact that the most basic requirement of sufficient *availability* of food is not fulfilled. Following the rule that the most basic problems need to be addressed first, my work will therefore focus on the problems of availability of food in Zambia.

In terms of the stability dimension, there is no overarching single indicator measuring the degree of (in)stability. This is unfortunate, but again confirms that stability or resilience of food security are topics that have not been sufficiently addressed so far and that my work could be a welcome addition to existing food security frameworks.

2.2 The Role of Maize for Food Security in Zambia

2.2.1 The Maize Sector in Zambia

Having established that ensuring food security is an enduring problem in Zambia, the next step is to find out what the role of maize is for food security in Zambia. I will therefore first discuss the history and current specifications of the maize sector in Zambia in general before then assessing its role for food security.

If there was one salient feature that all governments in Zambia over the last decades have shared, it has been the special emphasis they have placed on supporting the domestic production and consumer access to maize (Zulu, Jayne, & Beaver, 2007). Ensuring that the population had sufficient access to maize, which is *the* central staple food crop in Zambia, is even considered the basis for an implicit social contract between the government and its constituency (Jayne & Jones, 1997).

Hence, the first post-independence governments in the 1960's through 80's exerted tight control over the maize market, using maize policy as the major tool for welfare interventions intended to benefit especially the rural poor. However, as mounting financial problems and critical donors forced the government to abandon their heavy subsidy and trade control programmes, the maize policy changed towards liberalization in the 1990's. Yet, as international donors relaxed the economic policy conditions tied to their contributions some years later, the government sought to re-establish it's position as the major player in the domestic maize market and set up a new agency that will become essential for the remainder of our analysis: the Food Reserve Agency (FRA). While the FRA's original role was merely to buy strategic buffer stocks of maize to guard against price fluctuations in the just emerging private maize sector, one can see in figure 1 that from 2004 on, FRA progressively expanded this mandate up to a level where it actually traded the majority of maize in Zambia. (Govereh, Jayne, & Chapoto, 2008)

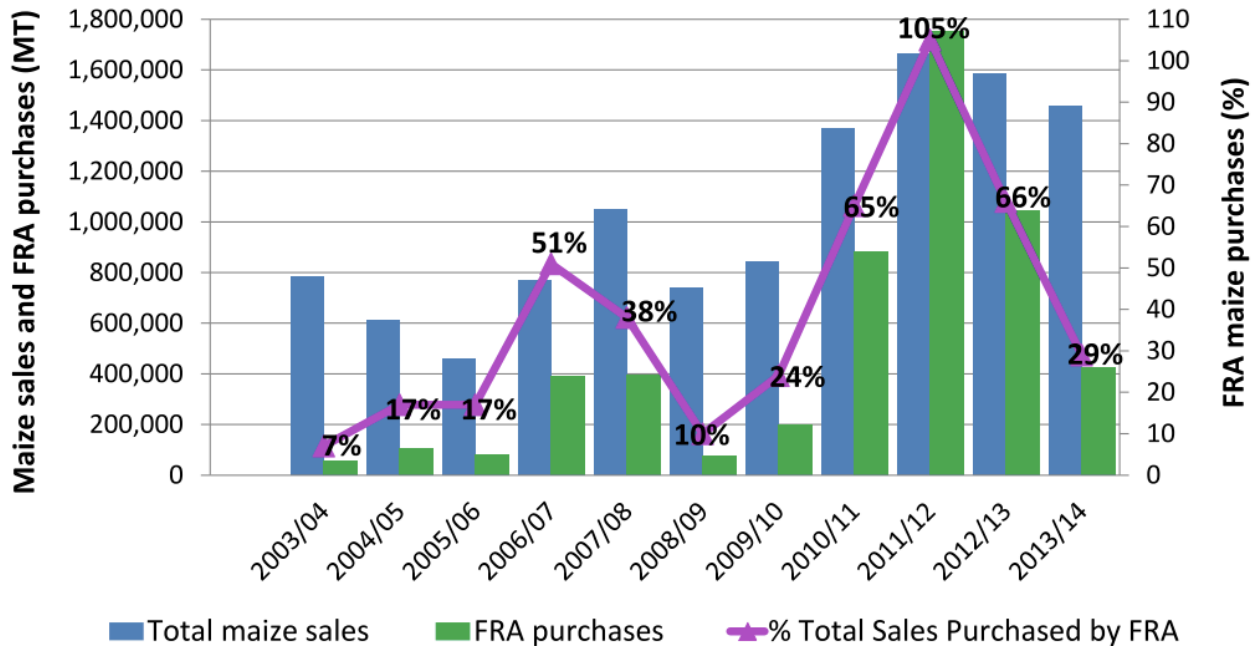


Figure 1: Domestic maize sales vs. FRA purchases (Kuteya, Sitko, & Inn, 2014: p. 8)

The result of this interventionist history is that these days, the maize market in Zambia can hardly be considered a “free market” working purely according to the laws of demand and supply. Rather, governmental actors exert strong influence by using a multitude of tools beside the FRA’s domestic purchasing activities to influence the maize market. These include: explicit export bans, limited issuing of export licenses, adjustment of import tariff rates, government imports of maize through FRA, sales of subsidized maize to large industrial millers, levies or bans on maize trade between different districts in Zambia, targeted fertilizer subsidies, etc. (N. M. Mason & Myers, 2011).

This long history of strong government support for maize, coupled with deeply rooted cultural perceptions and traditions, made and sustained maize as the single overwhelmingly important staple food crop in Zambia. Even in spite of recent shifts towards a greater crop variety, maize still accounts for over 50% of calories consumed in Zambia as of 2011 (FAO, 2015b) and is cultivated by 80% of farmers in Zambia (Zulu et al., 2007). Furthermore, Mason & Jayne, (2009) have found that there is a strong correlation in Zambia between low income and an above-average reliance on maize as the main source of

calorific supply. This means that especially the poorest, who are typically also the most vulnerable to shocks of all kinds, depend on maize over-proportionally for satisfying their basic calorific needs. As food insecurity is mainly a problem for the poorest strata of society, this means that maize is especially important to maintain food security for all of the population in Zambia.

After I initially wanted to create a model of the food value chain in Zambia in general, I quickly realized that every commodity's value chain has very distinct features that would make it impossible to represent them in one single chain. With too few time and resources at my disposal to build several value chain models, it was imperative to focus on the most important contributors to food security. For the reasons discussed above, this is clearly maize.

2.2.2 The Role of the Maize Value Chain

Having examined the nutritional role of maize in Zambia, it is clear that there can be no adequate food supply for Zambians at large without a sufficient supply of maize. But it remains to motivate why I chose to examine the maize value chain, i.e. clarifying which role it plays in ensuring a sufficient calorie supply to the population. Since the value chain represents the very mechanisms that actually get the maize from the farms scattered around the country's remote places to the non-subsistence consumers in the (semi-) urbanized regions, its role is obviously decisive: no distribution of food from producers to consumers can take place without a functioning value chain.

Field research suggests that food value chains are crucial when trying to address inadequate availability of food, as in Sub-Saharan Africa, post-harvest losses typically number around 10-23% of the original production (Hodges & Bernard, 2014). Bou Schreiber (2015) shows that this problem is especially pervasive in Zambia: the main maize purchaser FRA has mostly inadequate storage facilities, leading to heavy annual grain losses that become even worse when the system is shocked out of its equilibrium state, e.g. by unexpected bumper harvests.

Apart from the practical relevance of the value chain in maintaining an adequate food supply, there is also the circumstance that most of the academic literature on food security focuses on the production or consumption level (Stave & Kopainsky, forthcoming), while the intermediate value chain connecting both remains an apparently relevant but few understood “black box”. I thus want to fill this knowledge gap by building a causal model of the maize value chain in Zambia. As such, will my thesis complement Gerber's (2015) work about the production level and Bou Schreiber's (2015) study of food loss in the FRA, together helping to create a more holistic understanding of the maize sector in Zambia.

3. Methodological Framework

Two prerequisites for answering the research question are to devise an operationable framework for measuring resilience in a quantified SD model, and to define a clear and measurable indicator that serves as a proxy for food security in the context of maize supply in Zambia. These endeavours actually correspond to research objectives 1 and 2 and will be discussed in the following chapter. Moreover, I will further explore the relevance of my topic by investigating how susceptible the maize value chain is to shocks.

3.1 Definitions of Resilience

Resilience is a very broad topic that has received increasing attention in various disciplines over the last years. Yet, the use in manifold contexts and relative novelty of the concept contributes to a lack of conceptual clarity and the existence of many different competing definitions of resilience (Carpenter & Brock, 2008; Henry & Emmanuel Ramirez-Marquez, 2012). However, the concept is of course not used completely arbitrarily and therefore does have a certain core that is widely agreed upon. Olsson, Jerneck, Thoren, Persson, & O’Byrne (2015: p. 1) define this core as the agreement that “*resilience is concerned with the*

ability [of a system] to cope with stress or, more precisely, to return to some form of normal condition after a period of stress.”

In their endeavour to further clarify the nature of resilience discourses, Olsson et al. (2015) reviewed the systems thinking literature and concluded that there are essentially two types of definitions of resilience in use:

1. Resilience as “bouncing back”:

This definition stresses the quality of a system to withstand a disturbance and to recover from it, while preserving its structure. Insofar, resilience is seen as the ability of a system to resist forced structural change, while maintaining and/or recovering its central functions. (See also: Dalziell & Mcmanus, 2004)

2. Resilience as “bouncing back and transforming”:

This definition, contrary to the first one, understands the resilience of a system as depending on the ability to change its structure. The idea is that when a system is faced with a disturbance, it not only bounces back by recovering important functions, but also transforms its structure in a way that makes it better adapted to cope with the new environment.

These two lines of thought are therefore somewhat contradictory in how they view the role of preserving a system’s structure. Adopting the second view also creates further questions about the identity of a system: how big can the structural change be, so that the transformed system is still considered a “smart adaptation” of the original system, and when does the change become so big that the system essentially loses its identity and can thus be considered to have broken down and succumbed to the disturbance?

Summing up, we can conclude that there are competing, even partially contradictory, definitions of resilience and none can per se be said to be superior to the others. However, to achieve conceptual clarity in my research, it is imperative to choose a clear definition.

Since I want to find out how the supply of maize changes in relation to production shocks, I will have to look at short-to medium term changes that take place in a set of parameters within a few months to years. It is very unlikely that the basic structure of maize value chain will change significantly within this relatively short time, so that the component of structural change that is central to the second definition is not relevant. As methodology choices should be made according to their usefulness in reaching the research objectives, I will therefore adopt the “bounce back” definition of resilience.

3.2 Framework for Measuring Resilience in System Dynamics Simulation Models

Having established the general direction of how I intend to conceptualize resilience for my research, it remains to make this still rather vague concept measurable. Henry & Emmanuel Ramirez-Marquez (2012) propose a framework that operationalizes resilience as a function of time, which is well suited for application in simulation models. They remark that resilience always has to be understood as resilience *of a certain function in the system against a certain shock event*. This makes sense, as function A of a system might not be affected by a shock, while function B might break down completely – but when faced with a different shock, the system might be able to maintain function B, but not function A.

Henry & Emmanuel Ramirez-Marquez' (2012) framework therefore requires to specify the central functions of a system that one wants to evaluate, which they call “figures of merit” (FOM). The development of these FOM is then simulated in a no-shock base run and a shock scenario. The extent of change in the trajectory of the FOM between the base run and the shock scenario then indicates how resilient the system is in terms of that specific FOM to that specific shock. A graphic representation of this idea can be seen in figure 2.

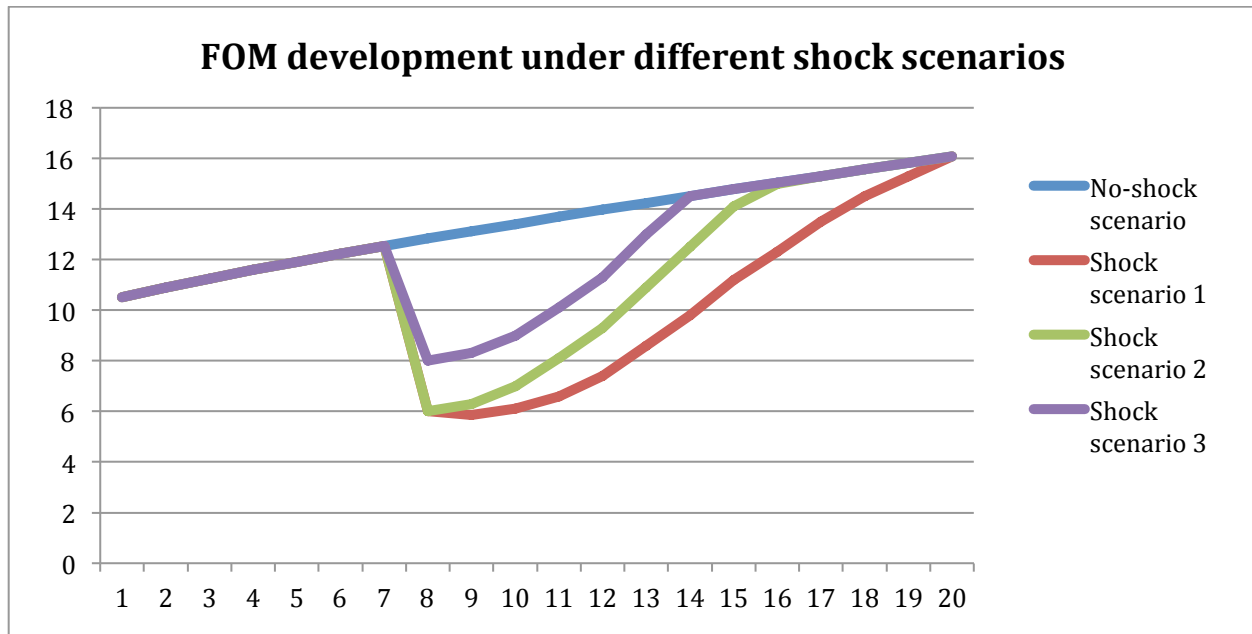


Figure 2: Development of FOM under different shock scenarios

Henry & Emmanuel Ramirez-Marquez (2012) further differentiate between two features of resilience in their framework:

- The **initial vulnerability**² is determined by how strong the initial impact of a system disturbance is on the FOM. In figure 2, this would be the drop in the scenario graphs occurring between times seven and eight. The FOM in scenarios 1 and 2 drops by 6,5 units, while the FOM in scenario 3 only drops by 4,5 units. The initial vulnerability of the FOM against the shock in scenario 3 would thus be smaller.
- The **adaptive capacity** is determined by how fast the FOM recovers from the shock by returning towards its original base run trajectory. The FOM shows the lowest adaptive capacity towards the shock in scenario 1, as it takes the longest time to return to the base run trajectory. While the FOM in shock scenarios 2 and 3 actually rise by a total of 6,5 units throughout the first six time steps after the onset of the shock, the FOM in scenario 1 only grows by 3,8 units in the same time.

² Note that in their paper, Henry & Emmanuel Ramirez-Marquez (2012) call this concept simply “vulnerability”, but I chose to make its name more specific so that it will not be confused with the general idea of vulnerability as the opposite of resilience.

The overall resilience of the system in terms of the FOM under consideration is therefore measured as the integral between the base run and the respective shock scenario run curve of the FOM. In figure 3, we can see how the different scenarios from figure 2 translate into integral values.

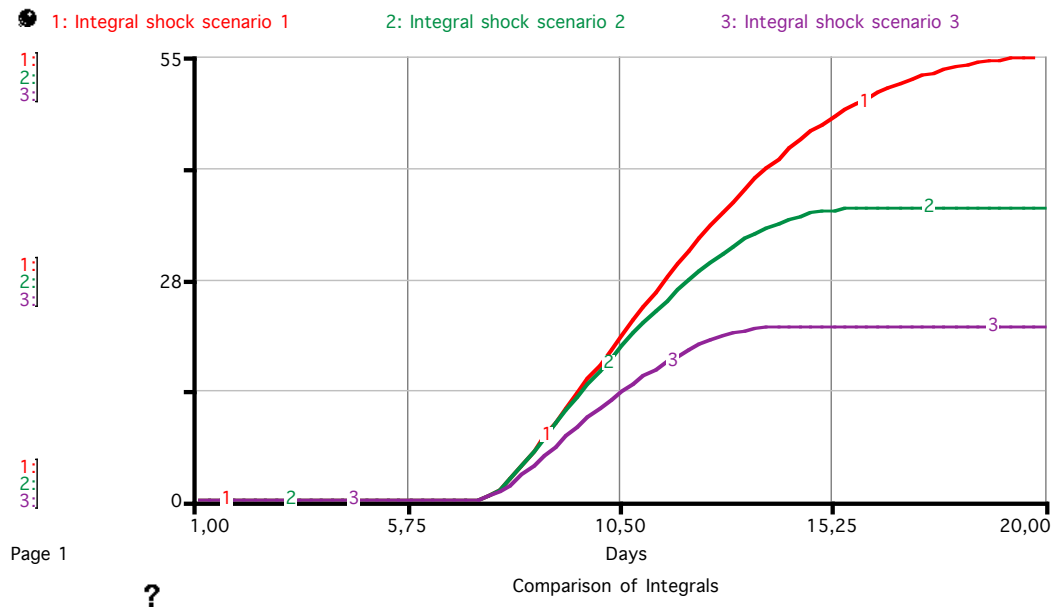


Figure 3: Comparison of Integrals

The differences observed between the three scenarios are neatly reflected in the development of the integral between the base run and the respective shock scenario runs. While the integrals for scenario 1 and 2 rise in the same fashion after the onset of the shock, scenario 3 exhibits a smaller initial rise due to its lower initial vulnerability. The differences in adaptive capacity can also be well observed in figure 3: the faster the gap between scenario FOM and the base run FOM is closed, the flatter is the rise in the integral. When the scenario FOM has fully recovered to the base run FOM's trajectory, the integral value stagnates. The framework thus described in this section will be the basis for measuring resilience in my analysis.

As a final remark on the terminology used, I want the reader to note that I will use the term "vulnerability" in the sense of Adger (2006: p. 269), who defines it as "the degree to which a

system is susceptible to and is unable to cope with adverse effects". In the light of our basic definition of resilience as the capacity of a system to successfully cope with shocks, vulnerability will be referred to as the opposite of resilience, so to speak the absence or resilience.

3.3 The Rationale for a Resilience Perspective on the Value Chain

Knowing what resilience is and how it can be operationalized for my purposes, it remains to be argued why resilience analysis is a relevant and useful theoretical framework for addressing food insecurity in the value chain. Adopting a resilience perspective on the maize value chain makes sense when Zambia in general, and the maize value chain in particular, are susceptible to shocks.

Several sources suggest that the generally weak political and economic institutions, poor infrastructure, heavy reliance on one main staple food crop and an exposition to sudden and strong changes in its climatic, political and economic environment, that it shares with most of its Sub-Saharan African neighbours, leave Zambia in in a position of high vulnerability on many levels. (Bertelsmann Transformation Index, 2012; Stockholm Resilience Centre, 2012; UNDP, 2014)

Since the maize value chain is a complex system influenced by political, economic, social, agricultural and climatic factors, the general vulnerability of the Zambian socio-economic system will also affect the value chain. More specifically, Stave & Kopainsky (forthcoming) argue that the food value chain, with respect to its function of delivering a sufficient food supply to the population, is susceptible to a variety of shocks even in developed countries. These include: transportation shocks (breakdown of the ability to transport food due to flooding or fuel shortage), energy shocks (breakdown of the ability to process maize due to a lack of energy), population shocks (loss of the workforce necessary to keep the value chain functioning due to hunger or disease), and resource shocks (impairment of maize production due to pests, droughts, floods). Furthermore, one could imagine economic shocks (impediment of the supply with input factors for maize production, processing and

transport due to price shocks), or in the case of Zambia's unstable political environment, political shocks (sudden stops of funding for fertilizer subsidies or FRA's maize purchase and storage programmes).

We can thus conclude that the maize value chain's capacity to ensure a sufficient maize supply for the population is subject to a variety of risks. Analysing the resilience towards these risks, and how it is related to the structural properties of the value chain, therefore appears to be a useful and relevant endeavour – as developing an understanding of the current situation is always the necessary first step towards improving it.

Apart from the topical relevance of a resilience perspective on the maize value chain, such a study would also constitute a desirable contribution to the theoretical discourse about resilience, as many authors argue that conducting more comprehensive case studies is the necessary next step towards greater applicability and practical usefulness of resilience research (Janssen & Anderies, 2013).

3.4 Measuring the Resilience of Food Security in the Value Chain in an SD Model

The last preparatory step before we can delve into the details of the model and the ensuing resilience analysis is to define the FOM that will serve as the basis for that analysis. To begin with, I want to remind the reader of two central results we have reached so far. Firstly, we found out in section 2.1 that there is simply not enough calorific supply in Zambia to fulfil the population's needs for an active and healthy life. Therefore, my indicator will focus on this most basic problem dimension: availability of food. Secondly, as discussed in section 2.2, due to the paramount importance of maize for the calorific supply and the lack of resources to model every food source's supply line, I will focus on maize as a proxy for food security.

With these two limitations, or guidelines, in mind I created a new indicator that is based on the ADESA and will serve as the central FOM for my resilience analysis. As laid out in table 3, ADESA is an indicator that measures the availability of food (DES) in relation to the

demand. While the availability is solely determined by the total amount of maize in the market, and does not account for problems concerning the access dimension, demand is determined by the Average Dietary Energy Requirements (ADER). The ADESA calculated as a ratio using the following equation: $DES/ADER$. So if for example, the demand for food per person is 3000 kcal/day, but only 2000 kcal/day can be consumed due to a lack of availability, the ADESA takes the value of 0,67. Corollary, a value of one for the ADESA indicates that demand is met completely, while a value of zero shows that no food at all is available.

The indicator I intend to use as the FOM for my resilience analysis is called “Adjusted Dietary Energy Supply with Maize” (ADESM). It is a modification of the ADESA in four respects: firstly, since we are just looking at the maize sector it is only concerned with maize instead of all food sources. Secondly, I am looking at the population of Zambia as a whole and therefore aggregate all individuals’ ADER to one national demand. Thirdly, my model includes feedback loops that alter demand as a result of changes in availability. The demand in the model is thus adjusted to represent parts of the access dimension as well. Fourthly, the availability of maize (equivalent to the DES) is measured in terms of consumption. This rests on the simple and plausible assumption that consumers will consume whatever amount they demand when that maize is available to them.

Like the ADESA, the ADESM is measured as a ratio between zero and one, with a value of one representing a full servicing of the adjusted demand, and zero indicating that no consumption takes place at all. Hence, the ADESM is calculated using the following formula:

$$ADESM = \frac{\textit{Maize consumption}}{\textit{Adjusted demand for maize}}$$

The *stability* dimension is incorporated into my analysis insofar that I will put the model under stress by running different production shock scenarios. The development of the ADESM under stress will therefore provide information about the stability, as well. Thus,

my analysis will encompass three of the four dimensions of food security, even though the focus is clearly on the availability dimension.

4. The Model

4.1 Scoping

As the purpose should determine the scope and nature of a model, I want to recall to the reader's attention that the purpose is to answer the research question, namely: What are the resilience properties of the maize value chain in Zambia towards production shocks in terms of ensuring sufficient maize supply, and how can the resilience be improved endogenously?

The main indicator for assessing this is the ADESM. The model thus needs to represent a plausible dynamic hypothesis for the behaviour of the ADESM – which then can later be used to examine the responses to production shocks and thus assess the resilience of the value chain towards these shocks. But before presenting my simulation model in detail, I want to discuss the rationale for the boundaries I have chosen for my model.

4.1.1 Vertical Scoping

When scoping a model of a value chain, it makes sense to start by looking at the definition of what a value chain actually represents. Kaplinsky & Morris (2001: p. 4) define a value chain as *„the full range of activities which are required to bring a product or service (...) through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use“*.

A value chain can thus be understood as a supply chain involving a multitude of actors that together supply the consumer with the final product she demands for consumption – in our case maize meal. It is called value chain because every activity in the process adds economic value to the original product, as it becomes more refined towards better meeting the demands of the consumers.

The next question to clarify is which inputs do we define as being the start of the value chain? In the case of maize meal, it makes sense to focus on maize, as it is the central raw material required to produce maize meal (along with the labour and capital needed to refine it towards meal). I thus define the start of the value chain as being the production of raw maize by farmers in Zambia. Adopting this product-based view makes it clear that the end of the value chain then has to be the consumption of the maize meal by consumers.

Since a central aim of my analysis is to uncover the possible frictions between the different actors in the maize value chain in Zambia, and to understand the dynamics of their interactions, I will define raw maize grain as the original input and not go into the details of its production. On the one hand this helps to achieve conceptual clarity, as maize production (transformation from labour, capital and seed inputs to maize grain) takes place within, and not in between, a single class of actors – namely farmers – and thus has its own peculiar logic. On the other hand, this helps to keep my thesis within a manageable scope, as the agricultural production sector alone is complex enough to constitute work for another research endeavour (Gerber, 2015).

4.1.2 Time Scoping

In terms of choosing the appropriate time step for my model, it was important for my model to be able to reflect the strong seasonality that occurs throughout the year in Zambia's maize sector. This seasonality is closely connected to the different stages of maize

marketing that appear throughout the maize marketing year³ in Zambia: the green harvest comes in in March and April, followed by the main harvest in May and June. While private buyers start purchasing maize from smallholder farmers right away when the harvest becomes available, FRA only purchases maize in the official government-announced marketing season, which usually lasts from June/July until the end of September or beginning of October (Nyanga, 2015b). While maize is usually well available in the months following the harvest (the “plenty season”), supplies dry up later in the year (Jayne et al. 2009). This happens either because the harvest was too small to service domestic demand, or because large FRA purchases have locked up all the remaining maize in the formal value chain, so that consumers in the informal chain are devoid of supply. This will be explained in greater detail later on. This series of discrete events and the observed seasonality thus required my model to run in months and include a number of discrete events so that it could capture the periodic dynamics of the maize marketing sector.

In terms of the length of the simulation, I chose to simulate into the future until 2020. Although shocks by definition happen quickly and within one year, I need to be able to see if there are ensuing changes in the patterns of behaviour of the model in the years following the shock. Furthermore, simulating several years into the future enables me to analyse the impact of different shock events happening in consecutive years. To provide appropriate historical calibration for the 6 years of future simulation, I am starting the simulation in the year 2004, when FRA started (again) purchasing relevant amounts of maize (Kuteya et al., 2014), thereby changing the structure of the Zambian maize market to the current state.

4.1.3 Geographical and Political Scoping

Since my aim is to understand the dynamics of the maize value chain in Zambia, it seems trivial to say that the geographical boundary of my analysis will be Zambia as a political,

³ Marketing year refers to the 12-month period, generally from the beginning of a new harvest, over which a crop is marketed. In the case of maize in Zambia, the marketing year thus starts in March when the green harvest starts coming in and ends at the end February.

economic and geographic entity. However, this has important implications for my model. While export and import decisions are made and financed according to internal dynamics, and are thus represented in the model, food aid is administered by external agents and thus not portrayed. This is because food aid constitutes a transfer of goods from other geographical areas and political entities that is ultimately at donor discretion and cannot be influenced by actors from Zambia. Since the research question is to find out what the resilience properties of the maize value chain *in Zambia* are, and what can be done in Zambia to enhance those, looking at food aid does not help answering the question and is thus excluded.

4.2 Overview of the Model

4.2.1 Central Stock-and-Flow Structure

The first task in creating the model was to define the central stock-and-flow structure of the value chain. Building on the research of USAID & COMPETE (2009), Keyser (2007) and Leathers (1999) Kang'ethe (2011) and Kirimi et al. (2011) about agricultural value chains in Sub-Saharan Africa, I conceptualized the main actors in the value chain to be:

- Farmers: producing the original product of maize grain
- Assemblers: acting as brokers for grain between farmers and millers
- Millers: milling and refining the grain to different types of meal
- Wholesalers: brokering the meal from large scale millers to retailers
- Retailers: selling the final product to consumers
- Consumers: purchasing and consuming maize meal

Transforming this information into a stock-and-flow structure of maize, the relations would look like displayed in figure 4.

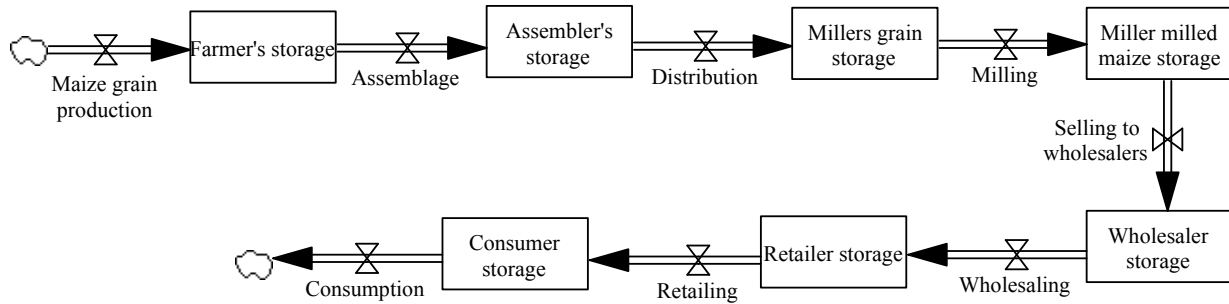


Figure 4: First conceptual formal maize value chain model

However, from the aforementioned sources it also became clear that the real dynamics of the maize value chain in Zambia were messier and less strictly compartmentalized than in the conceptual view presented above. The most important differences were:

- There is a second, less formalized value chain involving consumers buying their grain directly from farmers or grain retailers and milling it themselves using small hammer mills throughout the country (USAID & COMPETE, 2009: chapter 4).
- Farmers do not always sell to assemblers, some also directly sell to millers or even to grain retailers (Leathers, 1999: chapter 5).
- Wholesale and retail marketing activities can in Zambia not clearly be distinguished from each other. Many actors partake in selling meal from millers to consumers and they mostly do not fulfil clearly specified roles in the sales process (Nyanga, 2015b).
- The FRA has a very large impact on the maize market (N. M. Mason & Myers, 2011), which can, depending on political decisions for funding and purchase goals, completely alter the market dynamics in a given year (Kuteya et al., 2014).

Bearing these findings in mind, it was necessary to adapt the stock-and-flow from figure 4 to what is visible in figure 5.

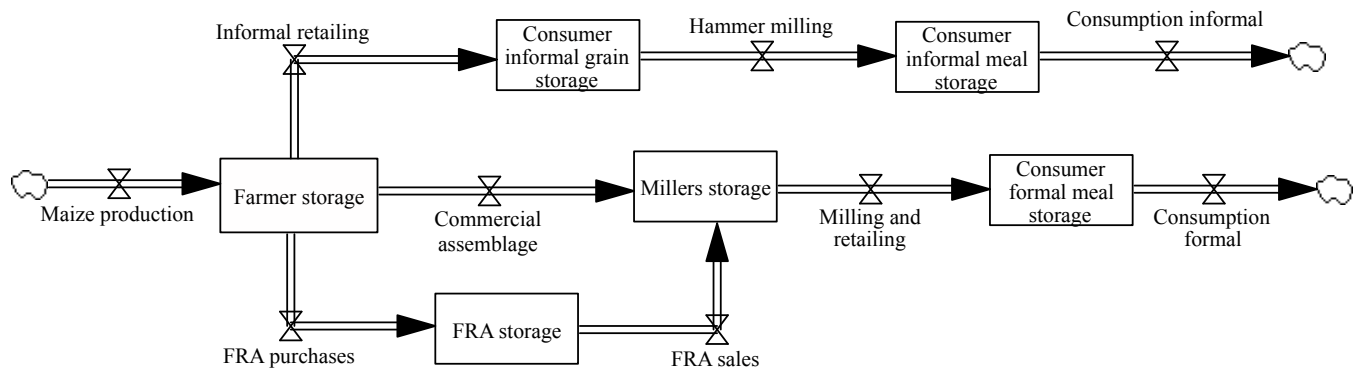


Figure 5: Adapted stock-and-flow structure maize value chain

As you will notice, the new structure represents the fact that there are essentially two value chains for maize in Zambia:

There is the more formalized avenue shown at the bottom in figure 4, involving farmers selling either directly or through small-scale assemblers to large commercial millers, these millers milling and refining the grain to different types of meal, selling it to retailers and these retailers then selling their bags of maize meal to consumers, who finally consume the product. The FRA is also involved in this avenue, as it purchases large amounts of grain from farmers, then selling it to large commercial millers later in the year. (N. M. Mason & Myers, 2011)

However, there is also the less formalized avenue, which is formed by consumers buying grain directly from farmers (in rural settings), or from informal grain retailers that purchase grain from small maize assemblers or farmers. These consumers then bring their grain to small hammer mills throughout the country to transform it into whole grain maize meal, which is then taken home and eventually consumed by them (Leathers, 1999: chapter 5). I will call this the “informal value chain” from now on, as the name represents the division between this avenue that involves many small-scale informal actors, and the other avenue discussed in the paragraph above, which includes bigger actors with more formalized organizational structures. The other avenue will thus be called “formal value chain”.

Apart from adding the informal value chain and FRA to the structure, you will notice that also the formal value chain has changed from the first conceptual sketch in figure 4. I will discuss the changes in detail below.

Since there is hardly any information about residence or adjustment times for many processes in the maize value chain in the literature, I relied on estimates by experts. My interview with Nyanga (2015b) concluded that urban retailers only stock maize for 1-2 weeks, as the majority of urban maize sales is done through street vendors or in big market spaces consisting of a congregation of small independent salesmen. With the residence time of the stock being so small in relation to the model's time step, I chose to represent retailing as a flow instead of a stock. I further added milling to that flow because milling takes only a few hours and is thus so negligible as a delay that it I felt it could be subsumed into the retailing flow in the formal value chain.

Concerning retailing in the informal value chain: in rural areas, there is normally no developed retail sector at all: local smallholder farmers just keep their grain stored and sell it directly to other people in the area at their farm gate. In urban areas, small-scale informal retailers buy grain from farmers or assemblers and sell it to consumers. (Nyanga, 2015b) I subsumed these activities in the "informal grain retailing" flow that brings the maize from smallholder farmers to consumers.

Furthermore, you will notice that the wholesale sector does not explicitly appear in the model any more. This is due to the finding that there simply is no developed wholesale market with wholesalers stocking meaningful amounts of maize or performing strategic purchasing and selling behaviour (Nyanga, 2015b). Instead, those small-scale entrepreneurs who perform functions closest to what one might understand as wholesaling (linking meal/grain producers to retailers), mostly act as mere agents of retailer demand for maize. Furthermore, in many cases the retailer himself purchases directly from the producer, especially in the informal value chain. It thus seems reasonable to subsume their activities into the retailing flow as well.

The first thing I want to draw attention to is the typical backwards-induced feedback structure of the value chain, where demand from downstream actors drives the demand from the next actor upstream in a cascade; this is represented by the positive links between the flows.

Next, we see two loops altering informal demand in response to availability. The counteracting loop C1 represents how informal consumers adjust their demand downwards in times of limited availability, and ensuing high prices for maize. Note that this downward adjustment is limited by a lower bound that corresponds to the minimum dietary energy requirements by FAO (2014).

C2 shows that, when not enough maize is available in the informal value chain to satisfy even the adjusted lower demand, the informal consumers will have to resort to buying the more expensive roller meal: this reduces demand in the informal value chain and increases demand in the formal value chain. This spill over of demand happens progressively stronger in the lean season as grain in the informal value chain becomes scarcer; and this process leads to fluctuations and an ensuing bullwhip effect in the formal value chain. When maize becomes available in the informal value chain again with the next harvest, the demand returns to the level of the original informal demand.

The link between the informal customer demand and the consumption is only represented as a dotted line because the consumption only depends on the demand in terms of its upper bound. However, the gap between demand and consumption is actually caused by the lack of maize supply coming through the flows from upstream. The loop involving this link is therefore not really a reinforcing loop and I thus did not label it accordingly.

Loop C3 represents FRA's policy to release its reserves when there is a supply shortage in the formal value chain to stabilize prices and supply. The feedback from the FRA sales to consumption is implicit in the flow structure bringing the maize from the FRA to consumers – the more maize FRA releases, the more is of course available to consumers in the long run for consumption. Note, however, that this feedback loop is limited by the

amount of FRA's reserves – once they have released everything in their storage, the loop cannot unfold any more impact.

Moreover, I want to draw attention to the importance of FRA's purchasing decisions for the behaviour of the value chain. The more maize FRA purchases, the fewer maize is available for private traders to buy from smallholder farmers – and the fewer they can buy, the smaller becomes the supply with maize for the informal value chain. This again has effects on when the demand spill over loop becomes active.

Finally, note that there are a number of stocks and delays involved in the route that the maize takes from harvest to consumption. These will become important later in my analysis, as they mediate the effects of production shocks on the ADESM.

4.3 Assumptions

Since any model is an abstraction of reality, it always has to rely on a set of assumptions that allow a simplification of the real world's complexity. As my model is no exception to that rule, I had to work with a number of assumptions that I will make explicit and discuss in this section.

4.3.1 Modelling Impact of Prices

A certain limitation of my model in terms of depicting reality one-to-one is the fact that price is not included explicitly. This is due to the fact that it proved impossible to get data about prices in such largely informal markets without extensive field research. However, I used information about relative availability of maize and permanent price differences as proxies for the effects of price. Whenever possible, I tried to ground these effects in expert estimates or academic literature. These implicit impacts of price will be presented in detail in the discussion of the model structure in chapters 4.4 through 4.8.

4.3.2 Post-Harvest Losses

Most physical losses of maize in the post-harvest handling of maize occur due to inappropriate storage that allows fungi and other pests to thrive (Hodges & Bernard, 2014). Although these losses can occur at almost any level of the value chain, I chose to only explicitly incorporate them into my model where they appear at a relevant scale. This means leaving out those instances where losses are negligibly low due to the use of good storage facilities or small residence time in the storage. This applies to the customer meal and grain storages, which only have residence time of 1 and respectively 3 months in my model⁴, and to the commercial millers which only stock maize for 1 month and can be assumed to have quite good storage facilities. The residence time for maize in all the storages I just mentioned stays below the critical 3 months-mark; and only after 3 months do losses really start to become relevant according to the African Postharvest Losses Information System (2015). Losses in the milling process are explicitly modelled according to data from academic literature due to their rather large extent.

4.3.3 Animal Maize Feed

Looking at the model, the reader might wonder why there is no explicit representation of the demand for maize as animal feed, which according to USAID & COMPETE (2009: table 8) does exist. The reason for that is twofold: first, the only large commercial animal products producer of the country “Zambeef” also possesses large amounts of farmland that can provide for their own animals’ dietary needs (Zambeef Products PLC, 2015). Second, there is a big amount of bran and germ meal production involved in the commercial milling process: 9% as estimated by Keyser (2007: table 49). According to Tambulukani (2014), livestock farmers only use bran or germ meal for animal feed – probably because it is cheaper than the meal from the kernel (which is the one sold to consumers), and to avoid political controversies about the use of consumer maize for animal feed.

⁴ To be precise, these are the coverage times for the respective stocks, but it seems reasonable to assume that customers are aware of the problems of long storage times for maize and thus consume maize according to the “last in first out” principle.

4.3.4 Exports

Maize exports in Zambia are strongly driven by discretionary political decisions rather than pure market dynamics, and are thus very hard to conceptualize in all their complexity and messiness. The government uses a multitude of tools, incl. export bans, to influence the external maize trade. (Dorosh, Dradri, & Haggblade, 2009; N. M. Mason & Myers, 2011). I therefore needed to make a few assumptions to be able to formulate the dynamics for maize exports. First, I assume that only FRA and big commercial farmers have the means to export, while smallholder generally do not due to their limited overall business capabilities. Second, I assume that the government lifts the export bans for big farmers only in years when smallholder production is well sufficient to meet domestic demand (see chapter 4.6.4 for more details). Third, since FRA is a political tool to ensure sufficient maize supply for the population, I assume that it would not make sense for them to export while there is still domestic demand for their maize. Following Nyanga's (2015a) observation that FRA starts trying to offload their excess stocks (those exceeding their desired buffer stocks) when they receive information about the new harvest through the new Crop Forecast Survey (CFS) in March, I assume that FRA sells/exports their excess stocks starting in March and finishing in May before their next purchasing season starts.

Finally, I have to note that FRA maize is often not competitive on international markets due to their above-market purchasing prices. However, since FRA's silo capacity is still quite limited compared to the volumes they purchased in the last years (Bou Schreiber, 2015), and losses in their non-silo storages grow exponentially with the residence time of the maize, I assume that FRA prefers to sell their excess stocks at a deficit rather than to have them simply rot away.

4.3.5 Imports

I assume that private maize imports are negligible, as they are generally discouraged and hindered through discretionary government interventions, inefficient bureaucratic processes and the fear of having to compete with subsidized FRA maize on the domestic

market (Dorosh et al., 2009). In my model, all imports thus run through FRA, which is the agency charged with carrying out governmental maize imports.

Concerning black cross-border trade with the neighbouring countries, there is hardly reliable information on it, but estimates show that the volume is so negligibly low in relation to the domestic market (Chapoto, Chisanga, Kuteya, & Kabwe, 2015), that it seems justifiable to neglect them in the model, as well.

4.3.6 Capacity constraints

The value chain in my model does, except for storage facilities in FRA, not feature capacity constraints. The rationale behind this is that consumer demand (except in the case of FRA) determines the quantities handled upstream in the value chain, and that per capita demand for the staple food maize is very unlikely to suddenly and significantly change its scope from one year to another. As such, actors in the value chain can well adapt to the long-term and rather smooth upward changes in demand, making it unlikely that they suddenly find themselves in a situation where an unexpected spike in total demand necessitates handling a significantly higher volume of maize and lets them face capacity constraints. Furthermore, even in the years of unusually high bumper harvest (2010-14), millers or retailers have not empirically been observed to have significant problems to process the requested amounts of maize.

4.4 Subsistence Sector

Subsistence production is maize that is produced and then consumed by the producing farmers themselves. It never enters the market and the value chain and is thus not relevant for my analysis. However, subsistence production is still important for my model insofar it satisfies a certain share of national demand. Fluctuations in the subsistence demand thus simply mean for my model that those 75% of smallholders who produce mainly for subsistence (Zulu et al., 2007) were able to satisfy their own demand for maize to a greater or lesser degree than in the previous year. Corollary, their need to top up their own maize stocks with externally purchased maize just becomes lower or higher by the same amount

that subsistence production fluctuates. The subsistence production is thus simply deducted from total demand (including a mark-down for losses occurring in storage and milling) to yield the demand for marketed maize.

4.5 Demand Sector

Since reliable data about maize demand in Zambia could not be found, I had to devise a way to calculate it myself. I did this the following way: multiplying the total population with the ADER for Zambia of 2112 calories/day (FAO, 2014) and with the ratio of calorific supply that is covered with maize (0,502 according to FAO (2015b)) gives the total demand for maize in kcal per day. Dividing this value by the calories per metric ton of maize (UNHCR, UNICEF, WFP, 2002: annex 5) and multiplying it with the number of days per year gives the yearly demand for metric tons of maize in Zambia. From this, I deduct the subsistence production in the manner explained above to get the total yearly demand for marketed maize in Zambia.

The next step is to divide the demand between consumers that prefer to buy grain (driving the “informal consumption”) and those who prefer commercially produced roller meal (driving the “formal consumption”). In general, low-income households prefer to buy grain over meal, as purchasing grain and bringing it to local hammer mills is distinctively cheaper than buying readymade commercially milled maize meal (Jayne et al., 2009: chapter 6). Since the rural population is generally poorer than the urban population, it seems reasonable to assume that the ratio of maize demand for grain is higher in rural than urban areas. Using data for maize grain vs. meal consumption in selected cities in Zambia from the latest available urban consumption survey (Nicole Mason & Jayne, 2009), I calculated a national average for urban consumers: when grain supply is not constrained, 33% of urban consumers prefer to buy grain and 67% prefer to buy meal (cf. appendix C.5).

For the consumers in rural areas, however, such micro-data is not available, wherefore I had to rely on expert estimates: Nyanga (2015a) estimated that 95% of the rural population prefer to buy grain – the 5% who resort to meal are a small class made up of

mainly of wealthy civil servants that have higher incomes and regularly travel to the city where they can buy maize meal. Using this information, I can calculate the monthly demand for grain (“original demand informal”) and the monthly demand for meal (“original demand formal”). I chose the term “original”, since the feedback from shifting availability and prices is not accounted for yet. An overview of the demand sector can be found in figure 7.

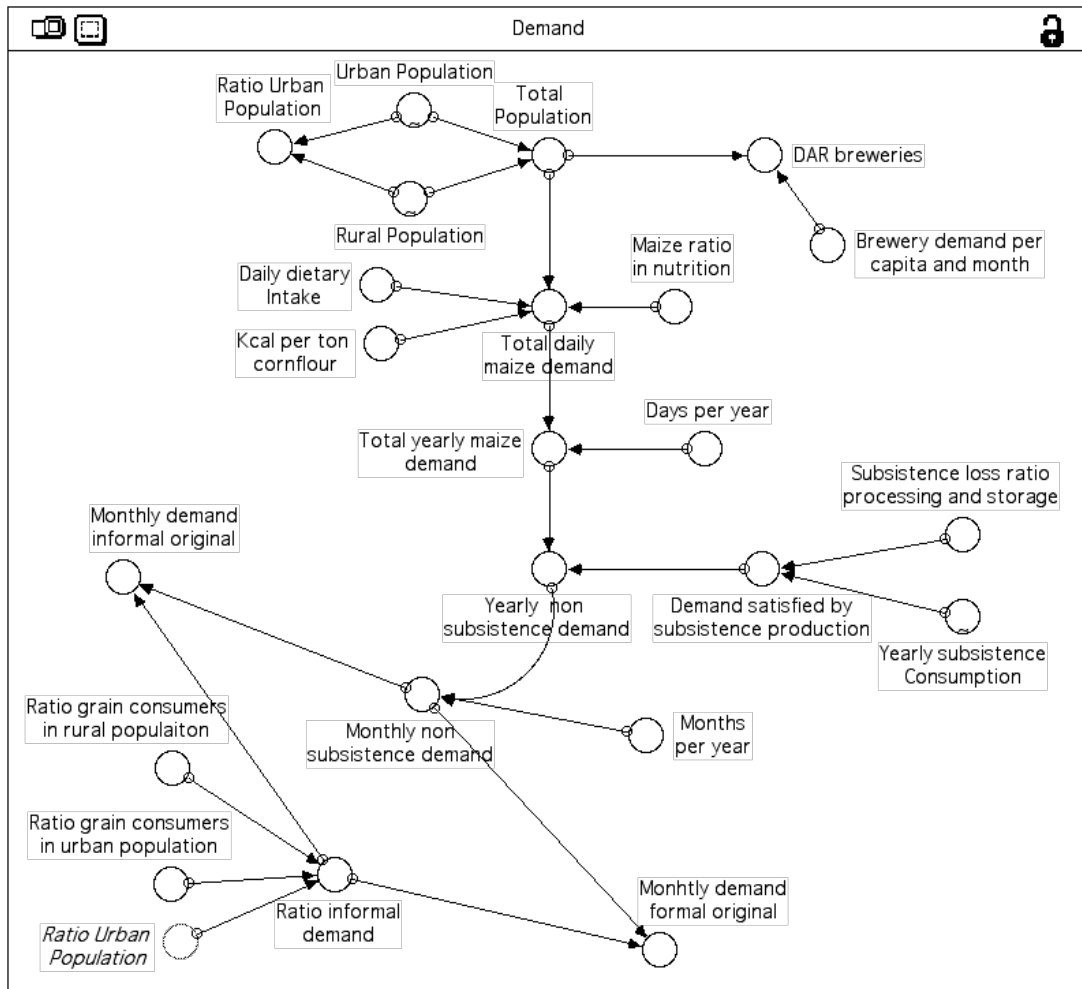


Figure 7: Demand sector

4.6 Formal Value Chain

An overview of the formal value chain can be seen in figure 8. The stock-and-flow structure is just as described in chapter 4.2. In the following section, I will explain the dynamics of the formal value chain in greater detail and establish the links to the literature by explaining why I chose to model the structure in the way presented. Since the value chain's behaviour is driven by consumer demand, I will start my explanation with the consumers and successively move upstream, just as the information feedback along the value chain does.

4.6.1 Millers and consumers

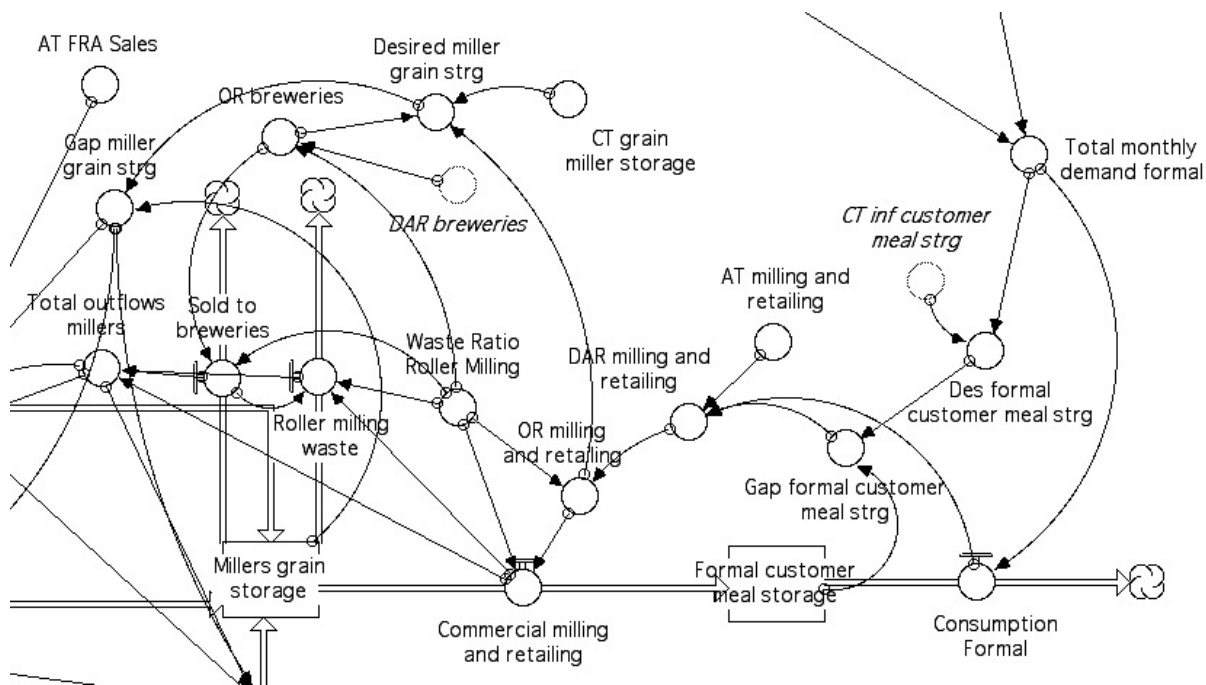


Figure 9: Millers and consumers

Since FRA's behaviour is mostly driven by highly discretionary political decisions (Chapoto et al., 2015; N. M. Mason & Myers, 2011), modelling their behaviour as a perfectly rational economic agent did not work. For the other actors further upstream (millers, retailers, consumers), however, I assume they exhibit typical behaviour of economic agents in a market, i.e. trying to maximize their utility in relation to the resources spent. I thus used an

adaptation of the well-established framework for modelling supply chain interactions, as laid out by Sterman (2000: chapters 17-18).

The original driver for behaviour in the formal maize value chain is the demand by consumers for maize meal. This demand determines the consumption of maize from their home storages, which is typically in the form of large bags of maize meal intended to cover 1 month's consumption (Nyanga 2015a). In order to keep up an adequate home storage of maize and to cover their daily consumption, consumers purchase maize from retailers. As explained in section 4.2.1, intermediate traders are subsumed into the flow from millers to consumers; so that the consumer's demand for maize refill directly governs the "milling and retailing" outflow from the millers' storage. Furthermore, millers also sell maize to breweries producing maize beer (USAID & COMPETE, 2009).

Since commercial millers typically produce roller meal of higher finesse, the maize bran and germ are separated from the kernel before milling, and about 9% of the weight is lost in the transformation from grain to roller meal. Adding other production losses to this, Keyser (2007: table 49) estimates that a total weight loss of 11% occurs in the roller milling process. I assume that commercial milling companies know their production process quite well and thus adjust their internal order rate upwards to account for the losses – so that their final output will match downstream demand. Their internal order rate then determines the millers' demand for maize grain: they want to cover one month of production and adjust for their outflows.

Millers have three options where to purchase the grain they need: directly from smallholder farmers, or from brokers that buy from smallholders themselves (subsumed in the "commercial maize assemblage" flow); from big commercial farmers; or from FRA. To reflect the fact that FRA maize is usually more expensive than maize from other sources (N. M. Mason & Myers, 2011), I modelled the millers' purchasing behaviour so that they prefer to buy from farmers first, and only if that source dries up, they turn to FRA for purchases. Furthermore, it can take longer to purchase from FRA due to bureaucratic procedures

centres, which feature more elaborate permanent storage facilities, such as sheds and silos. Sheds, however, still have quite high loss ratios in the medium term and only silos really keep maize largely unaffected by pests, moisture and fungi. (Bou Schreiber, 2015)

I therefore assume that FRA puts as much maize into their silos as their silo capacity allows. Once these are full, the next best storage option is to put the maize into the sheds. And only if these are also already full (something that only occurred in the bumper harvest years 2010-14 when FRA bought very large amounts of maize), maize is left in the local slab structures.

Building a model structure that could adequately measure the maize loss in FRA storages proved to be one of the trickiest parts of the work. After experimenting with different solutions it became increasingly clear that I could not work with the traditional way of measuring residence times (dividing a stock by its outflows), because the strong seasonality of my model lead to extreme fluctuations in the residence time that did not yield any realistic values. I thus adapted the age measurement structure from Bou Schreiber (2015) which proved to work well despite the seasonality in my model. It works the following way: when new maize is purchased, the current time (in months) is multiplied by the purchase volume (in weight), and the thereby “age-tagged” maize volume is accumulating in the co-flow structures visible in figure 10 above the value chain flows. Thus, dividing the maize currently on storage by the accumulated age-weight stock in the co-flow returns the average time when the maize on storage came into the stock (*average entry time*).

As maize is sold, old and new maize are assumed to be mixed for sale, so that on average, the maize sold (or moved to better storage facilities, in case of the first FRA stock) has the average age of all the maize in store. This procedure, as opposed to e.g. selling only the oldest maize first, is followed because the longer maize is on storage, the more its quality is adversely affected by moisture, fungi etc. – and the stronger quality is affected, the lower is the price for which the maize can be sold. Therefore, old maize is mixed with newer maize

in order to be able to sell it for a good price. For more details on this, see Bou Schreiber (2015). The outflow from the age-weight co-flow is thus not multiplied by the current time, but by the average age (*Average entry time*) of the maize in stock.

Now, to measure the average time that the maize in stock has actually spent on storage (the “relative age”), one simply has to take the difference between the current time and the average entry time. The relative age (i.e. time spent on storage) of the stock then determines the loss ratio, which is exponentially rising with relative age to reflect the exponential effects of spreading moisture, fungi and pest populations. Multiplying the loss ratio with the stock then determines the actual loss outflow.

Since Bou Schreiber's (2015) original structure was intended to measure the losses over one annual cycle, the outflow has to be divided by 12 months in order to transform the time horizon and return the correct loss values. In the case of the permanent storage structure, the combined loss ratio also depends on which ratio of the maize is in silos and which ratio is in sheds, since the two storage types exhibit distinctly different loss ratios (cf. appendix C.3).

FRA then sells its maize according to domestic demand to contracted millers, but not to retailers or consumers (N. M. Mason & Myers, 2011). This is important since it means that maize once purchased by FRA is effectively locked up in the formal value chain and cannot be supplied to informal consumers any more. If there is still excess maize left in FRA's storages at the end of the marketing year and it cannot be sold domestically, FRA exports the amount exceeding its desired security stocks. For more details on these exports, see section 4.3.4.

Furthermore, I assume that FRA wants to keep a certain share of security stocks to fulfil their original mandate, which is stabilizing the maize price with strategic maize reserves. However, I included a switch structure that sets the desired reserves to zero when we have a year with a structural maize deficit. This reflects that FRA, whose mandate is secure the

maize supply for the population, would not keep stocks locked up while domestic consumers demand more maize to fulfil their basic needs.

4.6.3 Smallholder Maize Sales

FRA, as well as millers and grain retailers, buys its grain from smallholder farmers. The dynamics of to whom and when smallholders sell their maize is critical for the overall model behaviour, as it determines how much maize goes into the informal vs. the formal value chain.

At large, smallholders have three options for selling their maize grain: either to informal grain retailers (who sell grain to consumers in the informal value chain), to commercial assemblers that broker grain to milling companies, or to FRA itself. Note that the popular notion that heavy FRA intervention is needed to enable smallholders to market their grain seems not to be true, as the past has shown that FRA and private maize buyers are easily interchangeable: as FRA purchasing activity goes up, private engagement is crowded out, but quickly fills the gap if FRA reduces its purchase volume (Chapoto & Jayne, 2011). This is reflected in my model by the fact that, given sufficient downstream demand, smallholders are always able to sell their maize to private maize brokers through the “commercial maize assemblage” flow – no matter how much the current sales deviate from previous sales.

For FRA purchases, there is an officially government-announced purchasing season that usually lasts from beginning/middle of June until the end of September or beginning of October, reaching the highest purchase volume around the middle of the purchasing season during late July and early August (Nyanga, 2015b). I modelled this as a normal distribution of annual FRA purchases over 4 months (from the beginning of June until the end of September).

However, since the bulk of FRA’s purchases occurs quite some time after the main harvest comes in, there is a danger of smallholders in my model selling too much of their production in the first months and not leaving enough maize for FRA to purchase. Such

model behaviour would ignore the strategic behaviour of many smallholders, who often sell some crops to private buyers early on to satisfy immediate cash needs, but generally prefer to wait until FRA starts buying in order to profit from their better price (Nyanga, 2015a). To reflect this behaviour, which carries the implicit assumption that FRA will always be able to purchase the amounts they want due to the higher prices they offer, I constructed a switch that limits smallholder sales to non-FRA buyers. The structure of that switch can be seen in figure 11 below:

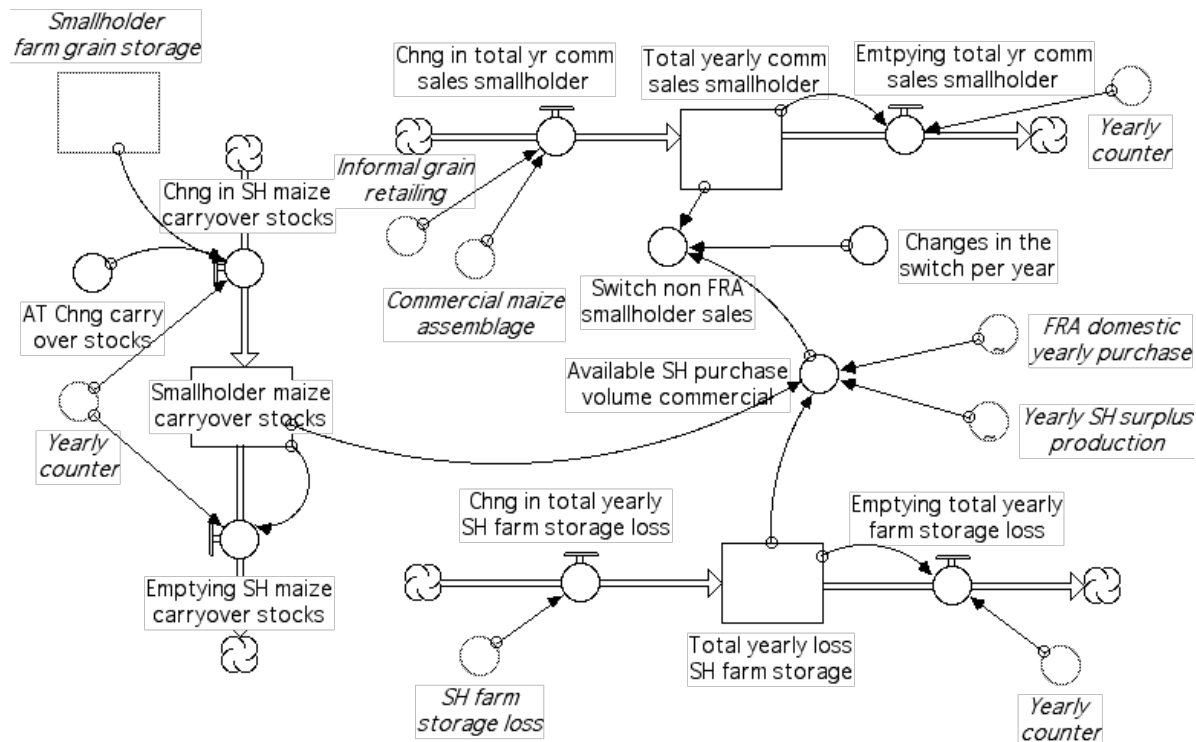


Figure 11: Non-FRA smallholder sales switch structure

The basic idea behind this switch is that non-FRA buyers of smallholder grain only purchase so much, that enough is left for FRA to satisfy its desired purchase volume. This is done by first calculating the total available smallholder grain for this year, which is the sum of any smallholder carryover maize stocks from last year and the harvest that will become available the current year. The available purchase volume for non-FRA buyers is then computed by deducting the desired FRA purchases and the storage losses from that total

available amount of available maize. Once the total non-FRA smallholder sales have reached this ceiling, the switch turns to zero, prohibiting further non-FRA sales by smallholders in the current year. The stock-and-flow structures are basically there to transform monthly into yearly data by accumulating monthly data and emptying it at the end of the year, so that we can work with the total yearly purchase volume.⁵

4.6.4 Farmers

The final actors at the upstream end of the value chain are of course the farmers. Building this part involved solving the recurring challenge to integrate data from different time scales and discrete events into my model. This proved especially tricky since System Dynamics is generally made to portray continuous, and not discrete events. A good example for how I went about this is are the harvest inflows: harvests volumes are usually reported per year, but in reality do occur only during a certain time in the year. To reflect this, I created a variable called “Yearly Counter” that used iThink’s COUNTER function to count the months of the year. I then used logical functions to represent the seasonality, such as the one for the *Smallholder Surplus Harvest*:

$$\begin{aligned} & \text{IF Yearly_counter} \geq 5 \text{ AND Yearly_counter} < 7 \\ & \text{THEN Yearly_surplus_production} * \text{Ratio_main_harvest} / \text{Main_harvest_months_per_year} \\ & \text{ELSE } 0 \end{aligned}$$

This allowed the flow to come in during a specified period of the year every time around (here in May and June). I used this approach for all three production inflows. The fact that much of my data was in years also explains why you will see many variables like “main harvest months per year” in my model that transform the time horizon from years to months.

Concerning the big commercial millers (visible at the bottom of the value chain), following Keyser (2007: p.65) I assume they only sell directly to big commercial mills and store their

⁵ There is a slight problem with this structure, as some losses occur after the ceiling has been reached, thereby effectively reducing the amount that FRA can buy. However, the deviation per year between the purchase data and the FRA purchases in the model are <0,05% and thereby statistically insignificant.

production for 6 months in appropriate storage facilities to be able to sell in the lean season and thus get a better price. According to Nyanga (2015b), these millers generally prefer to export whenever they succeed in lobbying for a lift of export bans with the government. This is because they are very competitive in their production due to economies of scale and rather advanced production methods, and can make good profit by selling to neighbouring deficit countries like Zimbabwe or the DRC Congo. Moreover, they fear competition by the unpredictable FRA in the domestic market.

To reflect the dynamics of the governmental export bans (N. M. Mason & Myers, 2011), I built the switch structure visible in figure 12 below.

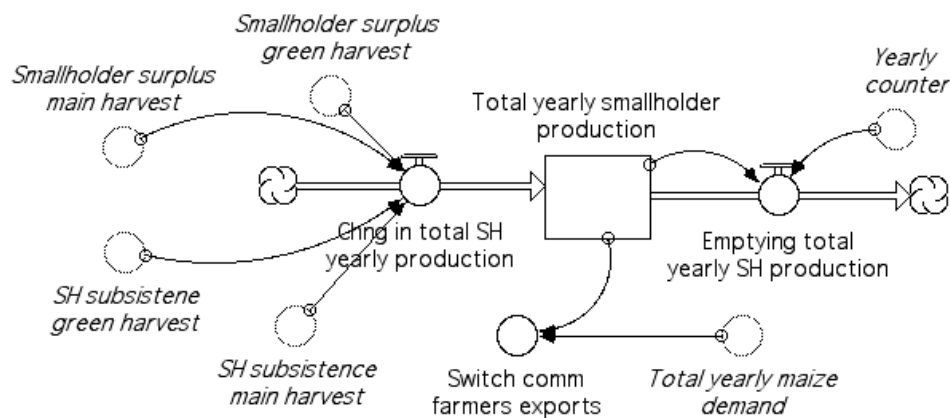


Figure 12: Commercial farmers exports switch

The basic idea is that the Zambian government assesses how much has been harvested by smallholder farmers in the current year, and if this amount significantly exceeds the projected demand, I assume that commercial farmers will succeed in their lobbying efforts for lifting export bans. In that case, they export their production. In years where the smallholder harvest is not judged to be sufficient to feed the domestic population, the government is assumed to insist on commercial farmers having to sell domestically and thus keep up the export bans.

seems reasonable to assume that consumers know about this loss and account for it with a rule of thumb, so that I presume they put a 5% mark-up on their meal orders here.

Yet, since consumers buy the grain themselves and then bring it to the hammer mill, the demand for purchasing grain comes from the original consumer demand and not from the hammer mills. The logic is the same as with the other inflows: according to a desired coverage time and the demand, a desired storage is computed. The gap between this desired and actual smallholder grain storage, together with orders accounting for the consumption outflow, determine the DAR for grain purchases and retailing (subsumed in the “informal grain retailing” flow).

To implicitly reflect the effect of rising prices on grain demand, I built a feedback loop from the informal grain retailing to informal demand. As grain gets scarcer, and thus more expensive, the ratio of demand for grain (DAR informal retailing) that cannot be fulfilled is rising. This is perceived by consumers and has an influence on their consumption. Since the consumers in the informal value chain are typically the poorer part of the Zambian population, it can be assumed that they lack the means to allocate significantly more money to their maize purchasing budget. Instead, they try to save money by stretching the time over which they consume a given amount of maize (Nyanga, 2015a). This means they are effectively reducing their daily consumption. However, as Nyanga (2015a) pointed out, there is a certain lower bound to that behaviour – people would rather sell assets or reduce other expenses before they go into starvation. I thus assume the lower bound for this effect is such that consumer never go below the Minimum Dietary Intake, as defined for Zambia by the FAO (2014).

4.8 Demand Spill-Over from the Informal to Formal Value Chain

Due to the structure of the market, there are times when grain in the informal value chain is simply not available any more. Consumers then have no choice but to switch from the cheaper self-hammer-milled meal to the more expensive roller meal. In that case, they stick to their lower daily maize consumption a fortiori (Nyanga, 2015a). However, 21,9% of

households also change to other carbohydrate sources, such as rice, bread or cassava (N. Mason & Jayne, 2009: Table 17)⁶. I modelled this by letting the gap between informal demand and consumption, after it is adjusted for the change of some consumers to other crops, spill over into the formal value chain's demand. Once grain becomes available again, the demand shifts back to the informal value chain, as the poor consumers are of course happy to go back to their cheaper self-milled maize supply.

We have now discussed the whole model and can, equipped with an understanding of the model structure, start to explore the behaviour in the next chapter.

5. Base Run

Before we are able to start answering the central research question by discussing scenarios and analysing the resilience of the model towards different shocks, it is necessary for the reader to acquire a good understanding of the central dynamics behind the model behaviour. To this end, I will first deliberate the assumptions used for the external inputs in section 5.1 and then discuss the resulting model behaviour in section 5.2.

5.1 Inputs and Assumptions

The model is running from 2004 – 2020, where the external inputs up to 2014 are based on data, while the six years from 2015 through 2020 are based on assumptions about the future behaviour of the following inputs:

1. Rural population
2. Urban population

⁶ Note that I took the data for Lusaka here, as it is statistically more likely to be representative for all of Zambia than the other, rather small or remote, towns listed.

3. Maize imports
4. Commercial farmers production
5. Smallholder surplus production
6. Subsistence production
7. FRA purchases
8. Desired FRA reserves
9. FRA Shed capacity
10. FRA Silo capacity

As these exogenous inputs play a big role in determining the behaviour of my resilience indicators, I will discuss them in depth in the following paragraphs.

Population

Concerning the population, I am assuming that it will follow the steady growth trajectory projected by UNDESA (2012), with the relative weight of the urban population growing due to urbanization processes. Population is an important parameter in my model, as it directly influences total demand, and thereby the ADESM.

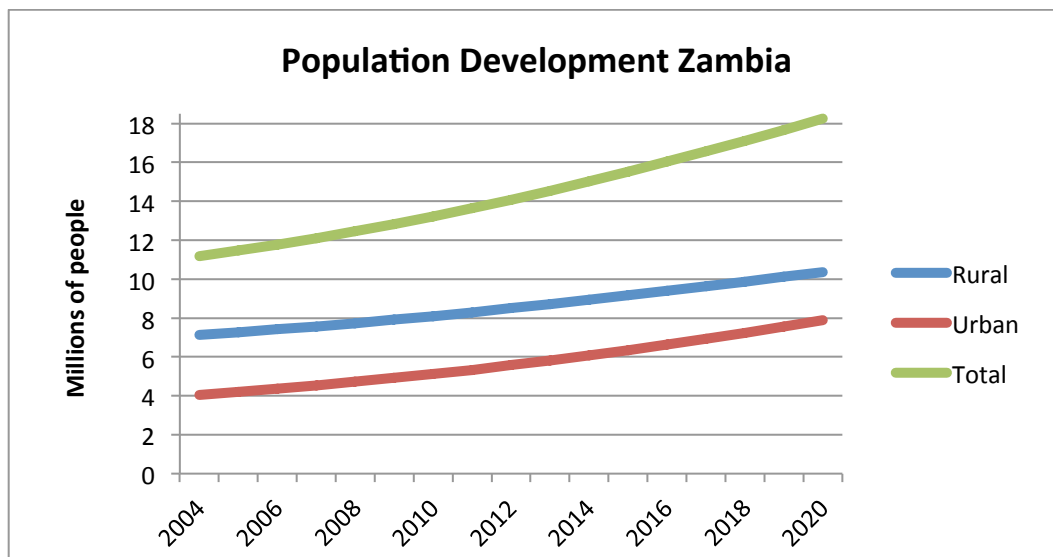


Figure 14: Population development Zambia

Maize Imports

For simplicity, and because I am interested in the endogenous development of the maize sector in Zambia without external influences, I assume that the trend of the last three years holds and no maize is imported.

Maize Production

My data for the base run comes from the base run of Gerber's (2015) production model. While he only splits his data in sold and not sold (i.e. subsistence) production, I further distinguish between sold production from smallholders and commercial farmers. To this end, I assume that the relation of 8% commercial and 92% smallholder production of the total sold production will stay constant for the next years. The development of the resulting yearly maize production that is fed into my model can be seen in figure 15.

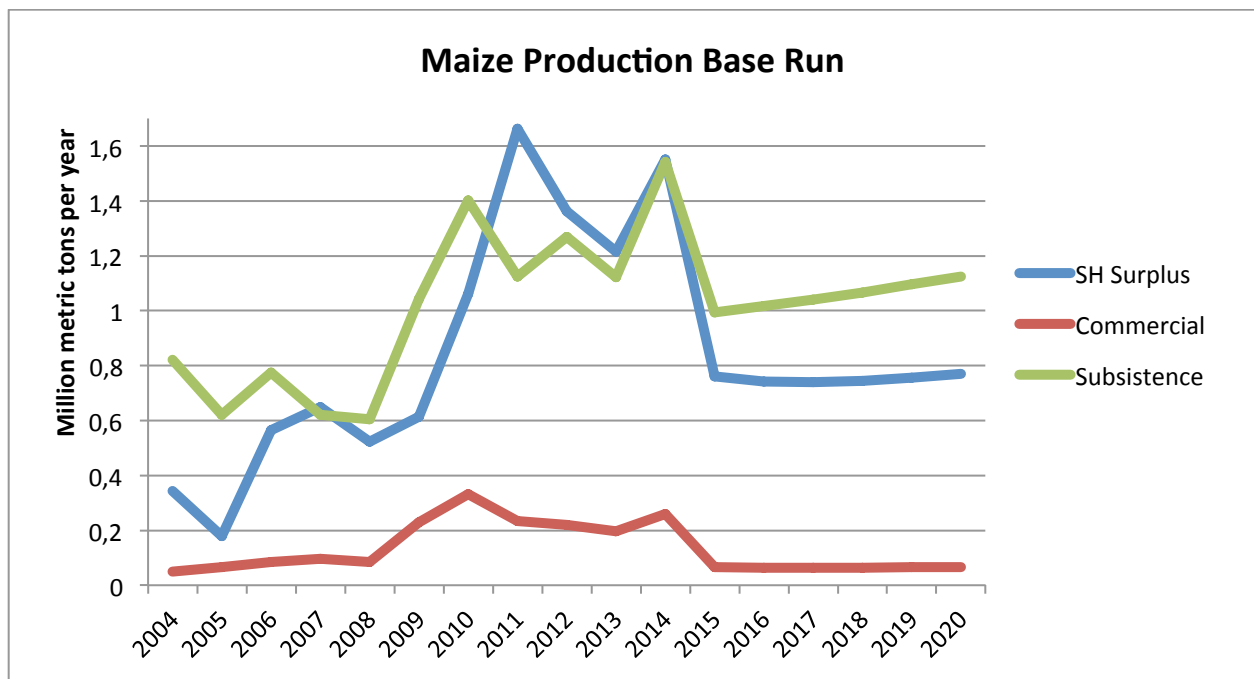


Figure 15: Maize production base run

FRA Storage Capacity

The information about FRA storage capacity comes from data collected and projections made by Bou

Schreiber (2015). As you can see, FRA has much more shed than silo capacity since silos, even though they preserve and protect the maize much better, are much more expensive to construct. Temporary storage capacity like slabs is assumed to be

unlimited, as it can easily and quickly be set up as it is needed.

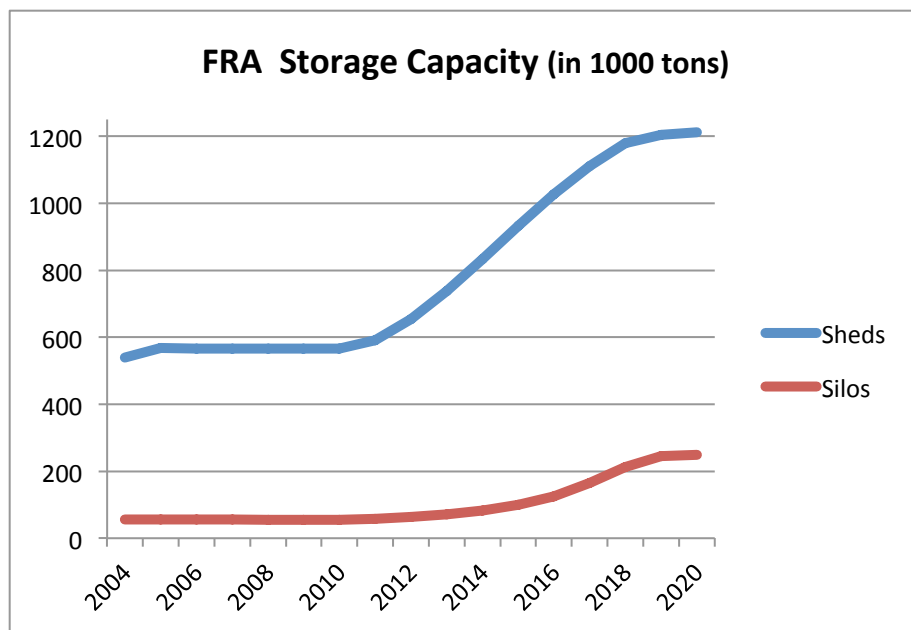


Figure 16: Shed and silo capacity FRA

FRA Policy Parameters

Concerning FRA purchase and storage policies, I assume that they scale back on the vast purchase volumes they had in the bumper harvest years from 2010-2014. On the one hand, these interventions cost the government a lot of money, an amount of spending that it might not be able or willing to sustain over the next years given its tight budget. On the other hand, the harvests in Gerber's (2015) forecast regress to the historical mean and the total maize volume traded simply becomes much lower, so that even if FRA wanted to keep buying a certain share of the production, they do not need to buy as much as in the last years. I thus assume that FRA aims to buy half of the smallholder surplus harvest in the coming years. Concerning the reserves, I assume that they want to keep 15% of their

purchases as security stocks. Saving only that much would also enable FRA to keep all their carryover stocks well preserved in silos. Note, however, that changes in historical FRA purchase volumes have been quite erratic at times – as such, predictions about FRA behaviour will always involve a large amount of uncertainty.

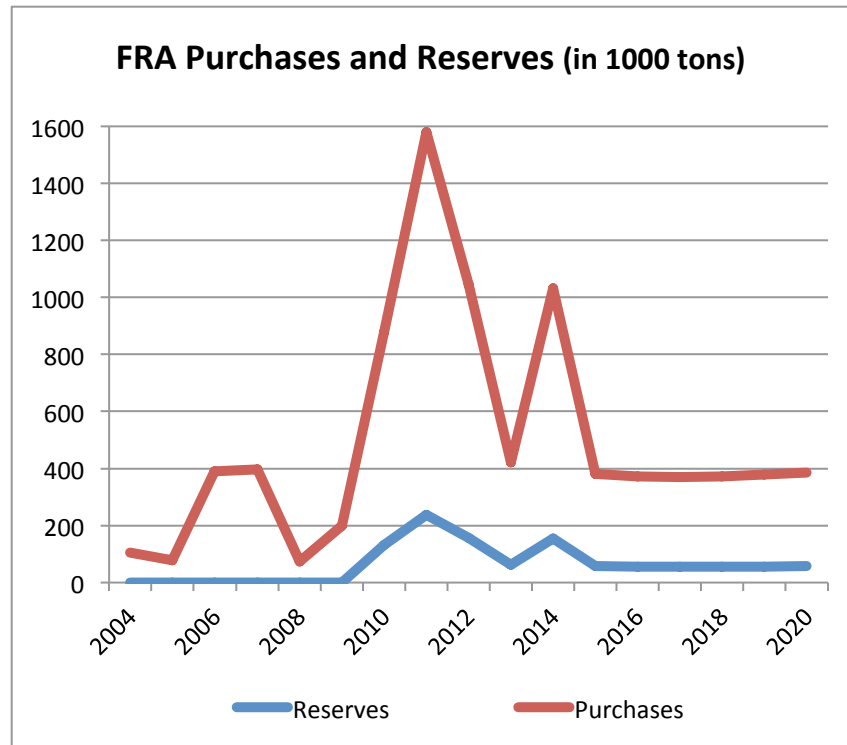


Figure 17: FRA reserves and purchases

The assumptions about the variables discussed will stay the same in all runs, unless otherwise is explicitly remarked. For details on the values and sources of the inputs mentioned, please consult appendix C.

5.2 Discussion of Behaviour

5.2.1 Dynamics Behind the Development of the ADESM

An analysis of the behaviour of the base run should be based on the evaluation of the behaviour of the central variable, which is the ADESM. Since the model runs in months from January 2004 on, the time units on the graphs should be understood in the following way: month 1 is the beginning (January) of 2004, month 2 is February 2004, month 13 is January 2005... and so forth up to month 204, which is December 2020.

A short note on the scale of all the iThink graphs showing the ADESM: the scale of the vertical axis is exactly ranging from one to zero. The maybe confusing second zero

appearing in the middle of the scale (cf. figure 18) is just there due to iThink’s setting to not show decimal numbers on that scale.

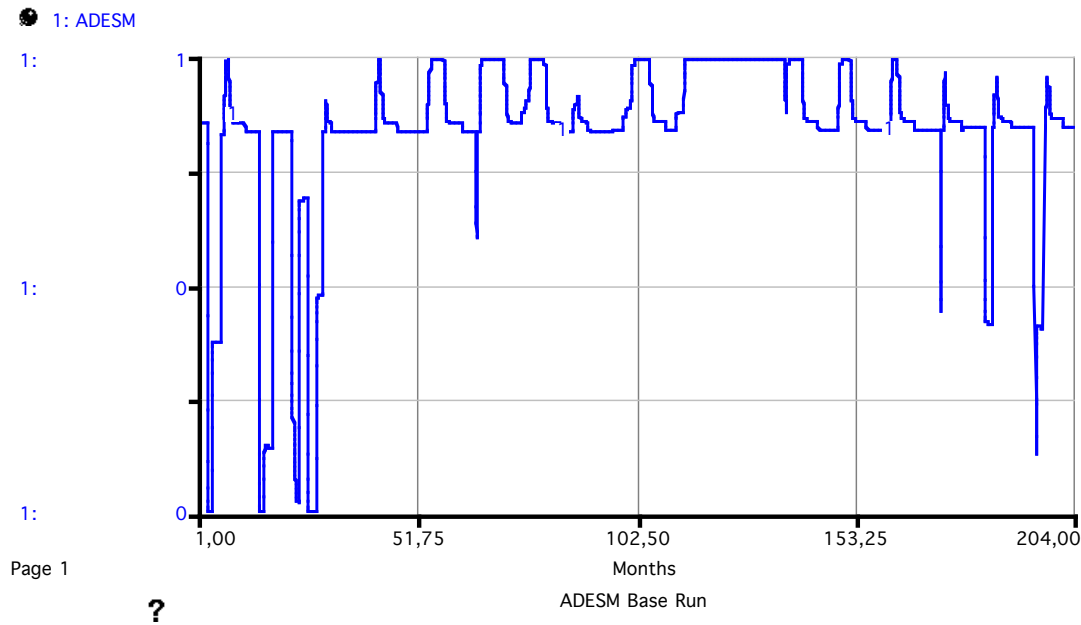


Figure 18: ADESM base run

The first thing that you will notice when looking at the ADESM’s behaviour in figure 18 is the strong seasonality: every year, with the exception of summer 2013 to summer 2015 (months 112-136), the ADESM fluctuates throughout the year. That has to do with the seasonality of the maize harvest: while there is some green harvest coming in every year in March and April, it only has a share of 7.5% of the total production. The main harvest then becomes available in May and June, which is when you see the ADESM spiking up. This behaviour reflects the typical alternation between the “plenty season” and “lean season” in Zambia (Nicole Mason & Jayne, 2009), where maize is well available in the months following the harvest and becoming very scarce in the months at the end of the marketing year. Since the first and last years of the simulation are years of structural maize deficit, the domestic maize consumption is used up after a few months following the harvest and the ADESM thus drops to zero. Note that Zambia did receive food aid in those years that most probably prevented the maize supply from completely drying up, but since we are focusing

on the internal dynamics of maize production these are neglected, as discussed in section 4.1.3.

The increasing size of the drops in the ADESM in the lean seasons of 2018-2020 (months 169-204) is because Zambia experiences a roughly steady yearly production from 2015 on, while the population gradually grows. The gap between production and demand therefore becomes increasingly bigger.

A little exception to that general seasonality pattern is the smaller spike that the ADESM shows from zero to about 0,6 in the months 23-24 (November-December 2005). This is due to the incoming harvest by commercial farmers that I assume to start selling in the height of the lean season in order to receive better prices. However, as their share of the total traded production drops over the following years, the impact of their production on the ADESM declines as well.

The reader will further notice that the ADESM often stagnates at a level of 0,84. This happens when the supply of maize grain for consumers in the informal value chain has dried up, making them lower their consumption and eventually start purchasing commercial roller meal from the formal value chain. The fact that this behaviour occurs even in years of surplus production, such as 2010-12 (months 73-96), is due to dysfunctional FRA policies.

A good year to explain the dynamics behind this phenomenon is 2010 (months 73-84): while this year actually features a good harvest that exceeds demand by a great margin, FRA purchases such vast amounts of maize (878.750 tons out of the total yearly smallholder production of 1.062.010 tons), that not much is left to purchase for private buyers. Millers, via small commercial maize assemblers, and informal grain retailers then compete for this relatively small amount of maize grain available to private buyers. Thus, their demand cannot be satisfied, which ultimately leads to supply shortages in the informal value chain.

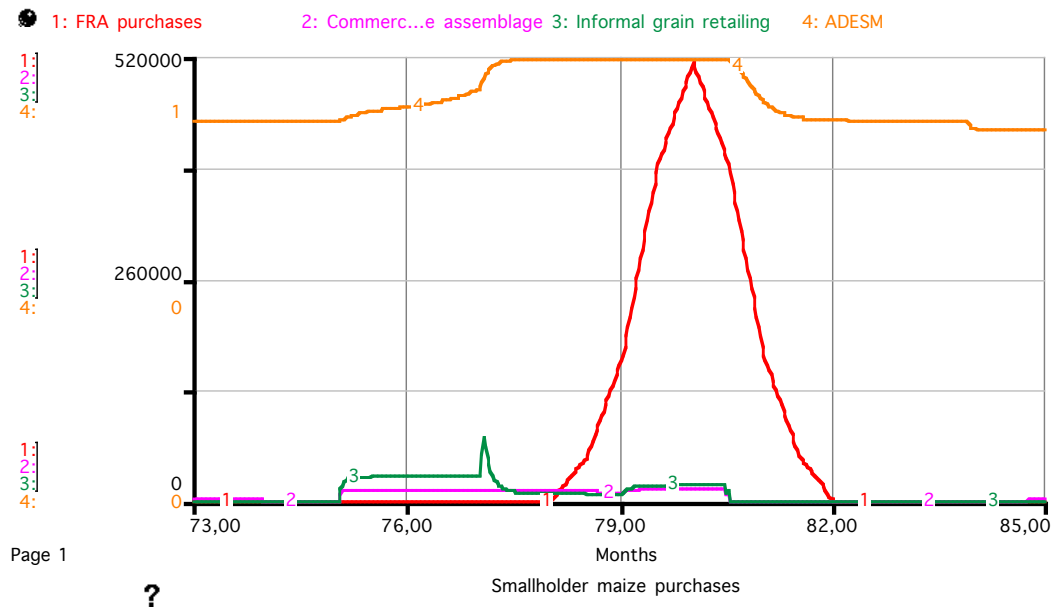


Figure 19: Smallholder maize purchases

In figure 19, we can see how this logic translates into behaviour: “commercial maize assemblage” and “informal grain retailing” reach zero around month 80. This means that all the maize that smallholders have not contracted to FRA and that was thus available for private buyers has been sold. As a result, the “non FRA smallholder sales switch” (cf. section 4.6.3) turns to zero. The flows of informal grain retailing and commercial maize assemblage therefore also drop to zero at that time. This means that the inflow of maize to the informal value chain stops and consumers respond by gradually lowering their monthly consumption, which makes ADESM gradually approach 0,84 as a response.

The problem with FRA’s purchase and sales policies is not just that they often dry up the informal market, but also that they purchase much more than they can sell or want to store as security stocks. This leads to long residence times of the maize in their storages and ensuing high losses. Hence, at the end of the marketing year, they are faced with a bad

choice: either let their excess maize rot away with exponentially rising loss ratios (cf. figure 20), or export it under unfavourable terms of trade.⁷

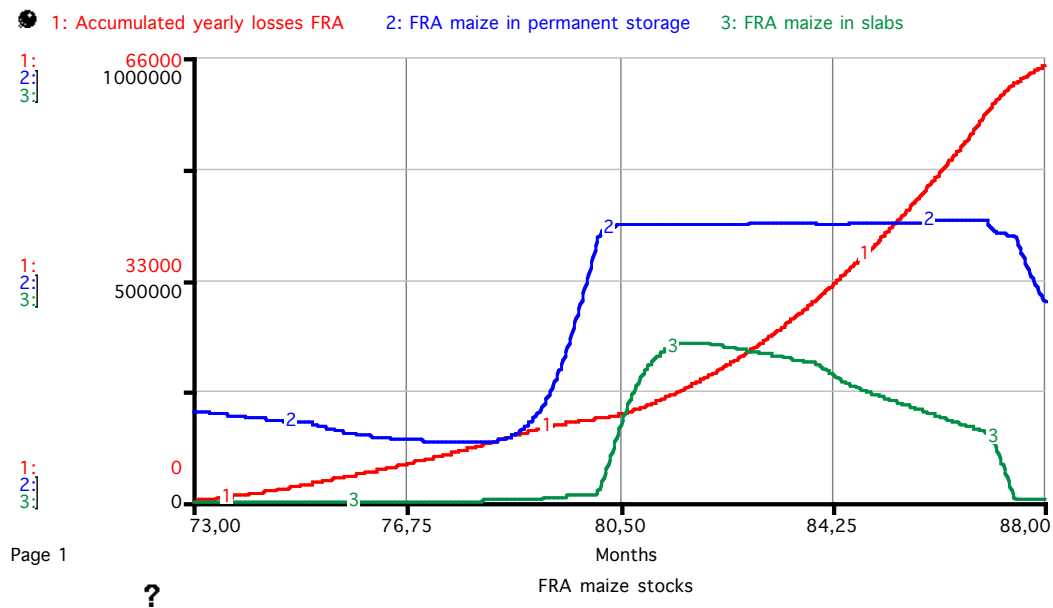


Figure 20: FRA maize stocks

An exception to the constantly recurring mismatch between demand and supply described so far is the time between summer 2013 and summer 2015 (months 113-140), where the ADESM in figure 18 nearly constantly displays a value of 1, indicating the full satisfaction of maize demand. This is due to the fact that in 2013 and 2014, harvests were very good and FRA purchases sufficiently low, so that the available purchase volume for private traders was high enough to service the demand from the informal value chain throughout the whole year.

As you can see, the key to understanding the model behaviour really is the distribution of the smallholder maize sales: they determine if the maize goes into the formal or informal value chain, or is locked up at FRA's storage facilities and lost to pests. Once the maize has entered one of the value chains from the smallholder stocks, or is sold by FRA, it is

⁷ These are due to the fact that FRA usually purchases maize at an above-market price that they cannot demand when selling maize abroad. They therefore often sell at a loss and it is just a matter of choosing the lesser bad for them in that situation.

processed and consumed according to the rules laid out in chapters 4.6 and 4.7. However, since the relative distribution of smallholder maize sales between the value chains is not only determined by supply, but also the demand for smallholder maize in the form of the *DAR informal grain retailing* and the miller's demand driving the *commercial assemblage* flow, I will explain their dynamics in more depth in the following section.

5.2.2 Dynamics Behind Private Traders' Demand for Smallholder Maize

First, let us examine the **informal value chain**. As demand for informal grain retailing (*DAR informal retailing*) is quite steady in years of constantly sufficient supply, the dynamics behind the seasonal fluctuations in this variable can best be understood when looking at a marketing season with changing availability of maize for the informal value chain. A good example is therefore the time from July 2012 to June 2013 (months 103-114).

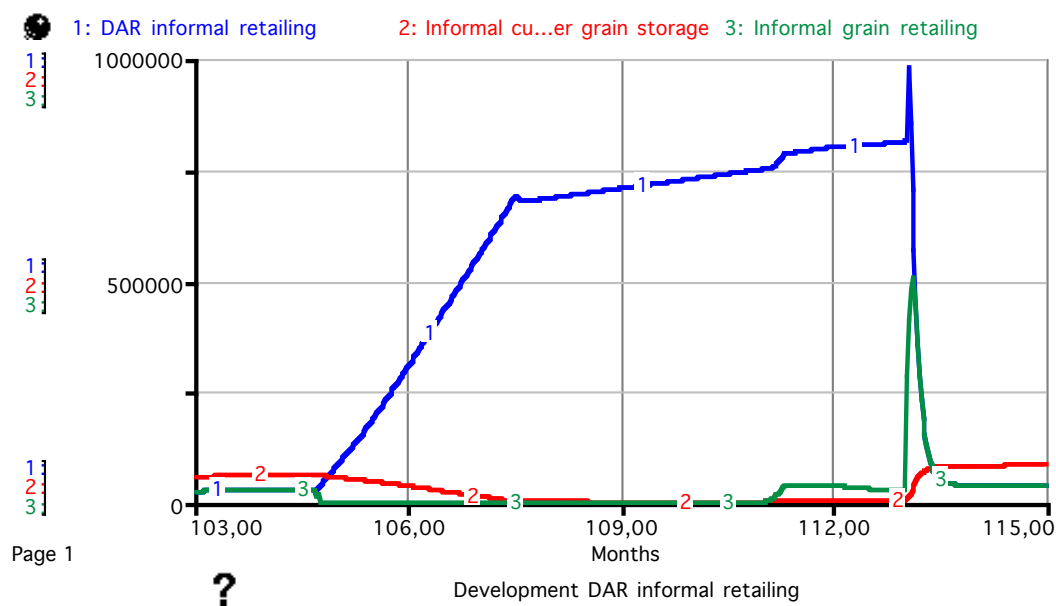


Figure 21: Development DAR informal retailing

As we can see in figure 21, starting in July where smallholder maize is well available (represented by the fact that the DAR and the grain retailing flow have the same value), the DAR informal retailing is steady and quite low. Since the informal customer grain storage is full and at the desired level, the DAR just aims to replace the outflow of losses and hammer

milling. However, later in the year (around month 104,5), grain supply dries up because the non-FRA smallholder purchase switch goes to zero, as can be seen in figure 22. Informal consumers now satisfy their demand by emptying their grain storage, while no new grain flows in, so that the grain storage is progressively depleted. As the storage becomes smaller, the gap grows bigger and the DAR shoots up because consumers wish to fill the growing gap between desired and actual grain storage (cf. figure 21). The growth in the DAR is greater than the gap because it is multiplied by the desired coverage time. Around month 107, the storage is completely empty and the DAR peaks. Thereafter, the DAR stays more or less steady at this high level, rising slightly with rising overall demand.

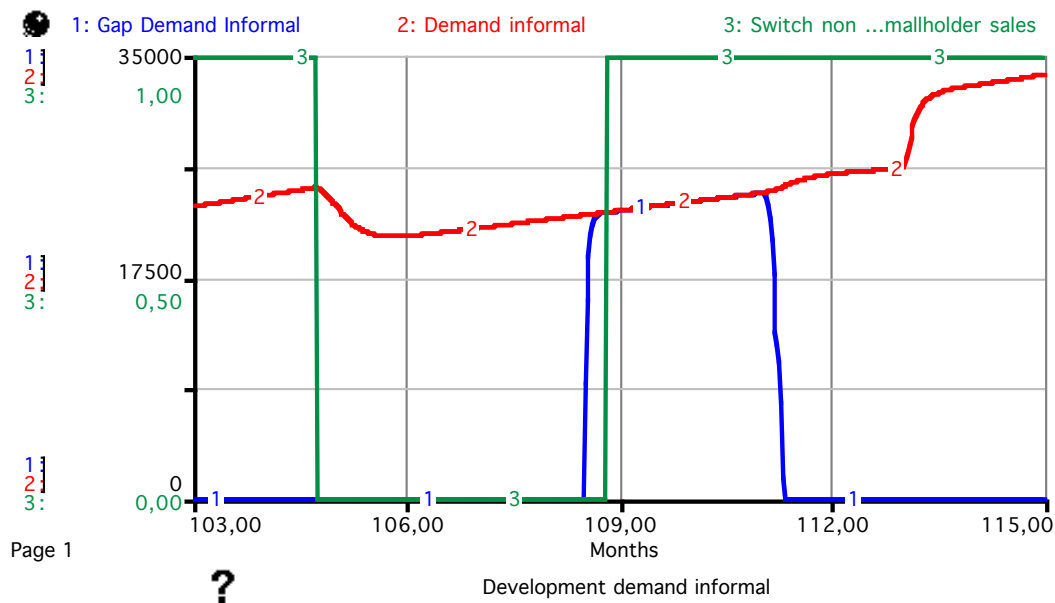


Figure 22: Development demand informal

While the non-FRA smallholder purchase switch turns to 1 again at the beginning of the new year in month 109, this does not help because all the remaining grain from the preceding harvest has by now been bought by FRA, so that smallholders have nothing to sell before the new harvest comes in. In month 108, all the stocks in the informal value chain have been emptied, so that the gap between informal demand and consumption shoots up and spills over into the formal value chain (cf. figure 22) – representing the fact that the customers from the informal value chain now have to resort to consuming roller

meal. The delay between this event, and the time when the grain storage is emptied (month 107) is due to the remaining maize in the informal customer meal storage that consumers can live off for a short time.

The depression in the informal demand between months 105 and 113 reflects that informal consumers reduce their daily consumption due to diminishing grain supply (cf. figure 22). This depression is also reflected in the DAR in figure 21.

However, in figure 21 we can see that in month 111 the new green harvest becomes available and the grain retailing begins again at the low level that the green harvest can supply. Consumers then change back from roller meal to their preferred grain supply and the gap drops (cf. figure 22). In month 113 (May), the main harvest becomes available and the supply is now so plenty that not only current consumption can be satisfied, but also the storage gap can be closed. The retailing flow thus rises to the level of the DAR, and as the gap is quickly closed they return to the initial equilibrium state (cf. figure 21).

Next, let us examine the dynamics behind the development of demand for smallholder maize in the **formal value chain**. Note that due to different adjustment times for the different sources that millers buy from, there is no uniform “DAR Millers” variable in the model. I therefore plotted the two variables making up the DAR, the gap between the desired and actual miller maize storage (*Gap miller strg*) and the sum of all the outflows of the millers’s grain storage (*Outflows millers*) instead.

Looking at figure 23, we can see that the formal value chain is in equilibrium state before month 108. The DARs just replace the steady outflows, steadily and slightly rising with increasing demand. The outflows of the millers are steadily higher than the DAR for milling and retailing because millers also sell maize to breweries and have to order more to make up for the losses in their milling process. However, in month 108 the informal demand spills over due the dynamics explained above and we can see a classical bullwhip effect (Sterman, 2000: chapter 18) happening: there is a step in the formal demand that leads to a higher spike in the *DAR milling and retailing*, and an even higher spike in the miller’s

ordering variables, if we look at the sum of the *Gap miller storage* and *Outflows millers*. This happens because the upstream actors not only increase their orders to service the higher demand they get from downstream, but also adjust their desired storage to be able to cover the new demand for a certain time. Thus, they order even more from their suppliers, who then repeats this pattern. That way, the original step in demand is amplified with every new actor.

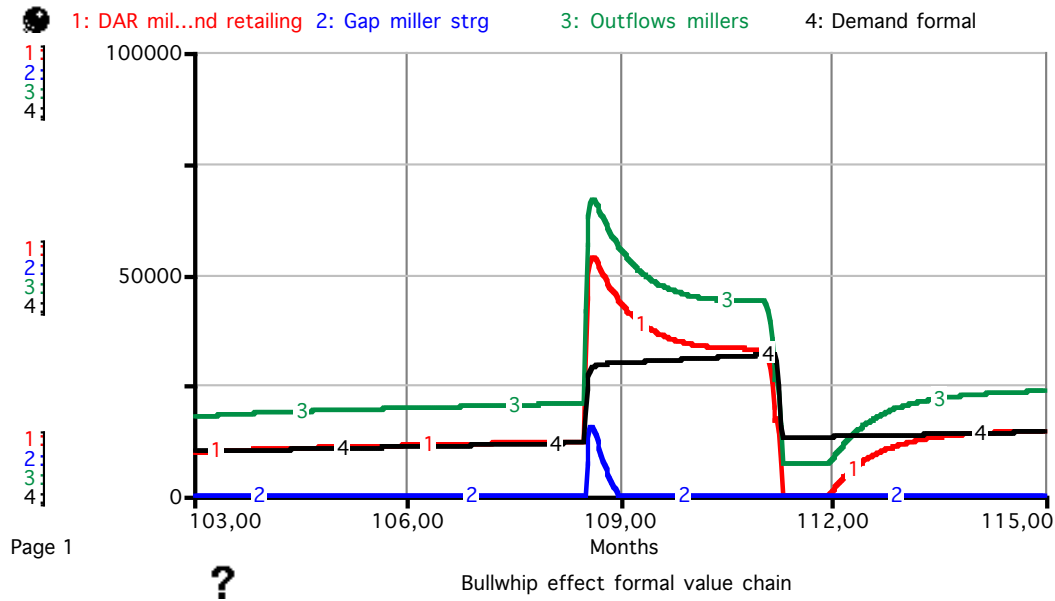


Figure 23: Bullwhip effect formal value chain

However, as the gaps between the new desired and the actual storage are successively filled, the DARs settle into a new equilibrium stage around month 110 (cf. figure 23). Yet, in month 111 the new harvest comes in and the informal consumers revert back to buying the now available grain. The formal demand therefore then drops to the initial equilibrium level and the DARs of the upstream actors go to zero (except for the millers outflows due to the steady difference explained above), as their storage is now much too big in relation to the current demand. Yet, over time they empty their storage towards the new desired level and start purchasing again so that the DARs go back the equilibrium value around month 114.

So how do the dynamics described play out in terms of the distribution of smallholder non-FRA sales between the formal and informal value chain? Looking at figure 24, we can see that the informal grain retailing flow becomes very big compared to the commercial assemblage in May (month 113) when the new main harvest become available. This is because the DAR informal retailing is much bigger than the outflows and storage gap of the commercial millers combined, and the informal retailing flow rises up to the level of its DAR when the necessary maize becomes available.

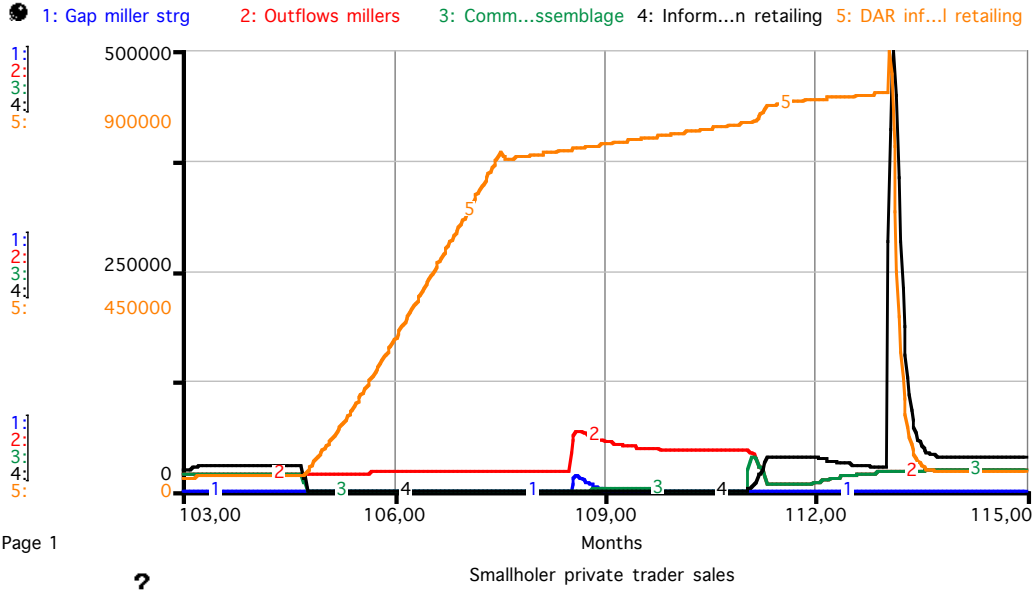


Figure 24: Smallholder private trader sales

The result of these dynamics is that a much larger share of the annually available smallholder sales for private traders is channelled into the informal value chain in years when there is no supply shortage in the formal value chain (like the one just described). After the gap in the informal grain storage is closed, the commercial assemblage and informal grain retailing flows settle to an equilibrium state where the greater overall original demand for maize in the informal value chain is reflected by the relation between the two flows (cf. figure 24).

Note, however, that the formal value chain exhibits a similar behaviour to what I described for the informal value chain in terms of a rising storage gap and ensuing higher demand in years where the formal value chain also experiences a supply shortage. In that case, the initial value of the “commercial assemblage” flow becomes bigger and thus the relative share of the maize that the informal value chain can attract becomes smaller than in the scenario described. We can thus conclude that the distribution of maize in between the value chains in the current marketing year is strongly affected by the availability of maize in the respective value chains in the preceding marketing year.

5.2.3 Summary of Behavioural Dynamics

Summing up, the following can be used as a rule of thumb for understanding the dynamics behind the fluctuations in our key parameter ADESM: it usually rises in May as the new harvest comes in, staying at a plateau value of one that indicates the full servicing of demand in both value chains. The grain supply then dries up either because the harvest was simply too small to satisfy total demand, or because FRA has locked up large amounts of maize in the formal value chain. ADESM then falls to a value around 0,84 indicating that people who would prefer to consume grain have to reduce their daily consumption and eventually resort to buying expensive maize meal. The time when this shift occurs depends on how much smallholder maize was channelled into the informal value chain. This in turn depends on the availability of maize in the formal and informal value chain in the preceding marketing year and is mediated through the dynamics described in chapter 5.2.2.

If the total harvest in the current marketing year was smaller than total yearly demand, the supplies in the formal value chain eventually also dry up, leaving the ADESM to fall to zero. If it was a surplus year, ADESM stays at 0,84. As the next main harvest comes in in May, the cycle begins again. Only when the difference between smallholder surplus harvest and FRA purchases is big enough to allow private traders and grain retailers to satisfy demand for grain all year round, the ADESM stays at 1 throughout the whole year.

The sales by commercial farmers later in the year and the incoming green harvest in March and April do bring some relief in the lean season, but they generally are rather insignificant due to their small size in comparison to total yearly harvest and demand. Furthermore, as commercial farmers only sell to the formal value chain, their production does not help to reduce the gap in demand in the informal value chain, and thus will not change the value of the ADESM if it is at 0,84.

One more important determinant of the ADESM's behaviour is the existence of carryover maize stocks from last year. If the current year shows a structural maize deficit, the consumption of stocks that have been accumulated in a better preceding year can stabilize the ADESM. I will come back to this in more detail in chapter 8.3.

6. Validation

To have confidence in the results of my study, it is necessary to be confident that the model I am using to generate those findings is valid. Model validation in System Dynamics is mostly understood as the gradual process of establishing confidence in the soundness and usefulness of a model (Forrester & Senge, 1980). As such, it was an on-going process that I went through when building and working with the model. However, the results of this process need to be formally demonstrated to the reader, to which end I use a set of standardized validation tests.

A limitation in terms of validation is that there was no reference data for my central variables, including most notably the ADESM. I thus cannot use the most prominent tool of validation: matching data and simulation results for the reference mode of behaviour. However, in his seminal paper on validation in SD, Barlas (1996) outlined a whole set of

other test that are able to establish high confidence in a model, which I will employ in this chapter.

6.1 Direct Structure Tests

Direct structure tests are test that assess the validity of the model structure through direct comparison of available knowledge about the real system with the model. They do not involve simulation

6.1.1 Structure and parameter confirmation test

This test requires the comparison of the model with available knowledge about the real system. I approached this by grounding every relation and parameter value in academic research, reliable numerical databases, reports by political organizations such as the UN, or if that was not available, expert knowledge. In case where direct information about a relation or parameter was not available, I used plausible assumptions that were themselves grounded in other sources of the types just described. The detailed justification for relations, parameter formulations and values used in the model can be found in the discussion of the model in chapter 4 and the documentation of the model in appendix A.

6.1.2 Dimensional consistency test

This test requires all variables in the model to be dimensionally consistent. As can be seen in figure 25 below, my model passed the automatic unit consistency test in iThink and thus conforms to these standards. Details concerning the equations and units used in the model can be found in appendix A.

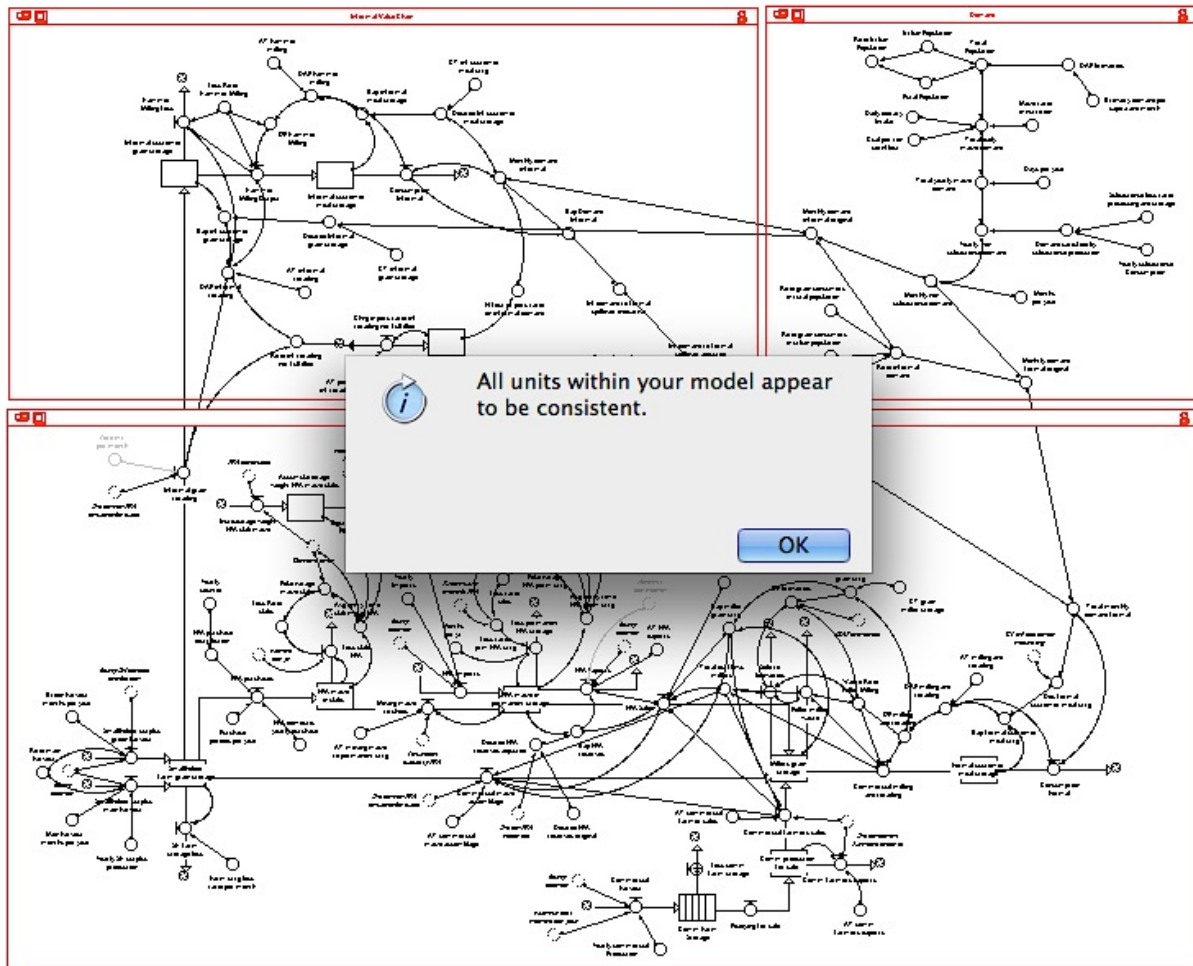


Figure 25: Dimensional consistency test in iThink

However, Barlas (1996) rightfully remarks that this test is only relevant in conjunction with a successfully passed structure confirmation test, meaning that the model should not contain meaningless “dummy variables” to make it consistent. As the reader will notice looking at my model, there are a number of variables that on first sight might seem suspicious to be such dummy variables, e.g. the “main harvest months per year”. Yet, they do actually have a meaning and function on their own, as they transform variables from one time scale into another – e.g. yearly data into monthly output so that the seasonal dynamics can be reflected. E.g. the “main harvest months per year” variable’s value of 2 months serves to distribute the yearly production in two even parts over the two main harvest months in Zambia, May and June.

6.1.3 Direct Extreme Condition Test

This test involves “evaluating the validity of model equations under extreme conditions, by assessing the plausibility of the resulting values against the knowledge/anticipation of what would happen under a similar condition in real life” (Barlas, 1996: p. 190). As opposed to the behaviour extreme conditions test, this test does not involve simulation. In building the model, I always tried to keep in mind the impact of extreme conditions and designed all the equations so that they would behave logically. Even though it would take up too much space to go through all the equations here, they can be visited in appendix A by the interested reader and inspected in detail there. At this point, let us look at the Desired Acquisition Rate for roller meal by consumers (*DAR_milling_and_retailing*) as an illustrative example. I used similar structures several times in my model and they are crucial as they drive the behaviour of the value chain through passing the information feedback from upstream consumers to downstream suppliers and producers.

The equation for *DAR_milling_and_retailing* is the following:

$$\text{MAX}(0, \text{Consumption_Formal} + \text{Gap_formal_customer_meal_strg} / \text{AT_milling_and_retailing})$$

Let us now assume two extreme scenarios for this variable:

- a) The demand becomes extremely high. This will also increase the gap between the desired and actual customer meal storage, as the desired meal storage is a function of demand and coverage time. What will happen to DAR is that both the gap and the consumption (if there is enough maize to consume in the stock) shoot up, strongly driving up the DAR as well. This behaviour seems plausible.
- b) The demand drops to zero. This would lead to zero consumption and actually a negative gap, as the desired meal storage would also become zero while the stock still holds a certain positive value of maize. Zero minus a negative value would of course make the DAR become negative, which would not make sense since you cannot order negative meal from a miller or retailer. I thus added a MAX function to

prevent this potentially illogical behaviour. With this addition, the variable value now becomes zero and would be plausible.

The formulation thus passes the direct extreme condition test. It has in similar form therefore been used for other desired acquisition rates in the model as well. In the case of the millers' acquisition, I do not compute a single DAR because adjustment times are different for their different suppliers. However, each flow has been set to be a uniflow, which is the equivalent of a MAX function, in order to ensure the same plausible behaviour discussed here.

6.2 Structure-Oriented Behaviour Tests

Structure-oriented behaviour tests are used to assess the validity of the structure indirectly by scrutinizing how the behaviour changes under a number of different conditions. If the behaviour changes are plausible in relation to the changes in the conditions, confidence in the model's structure can be gained.

6.2.1 Extreme Conditions Test

This test requires assigning extreme values to selected variables and evaluating if the model behaves plausibly in response. The model behaviour is deemed plausible when it reflects how the real system would react to such extreme changes.

Although I applied this test to many sub-structures of the model, it would take too much space to discuss all of these here. Luckily, we can assess the plausibility of all the sub-structures by analysing the behaviour of the model as a whole, since the entire model will only behave correctly if the sub-structures work correctly as well. As smallholder production is probably the highest-impact parameter in my model, it makes sense to use it for extreme-condition testing. To test the response to extremely low, as well as high harvests, I set production to zero with a STEP up to 3 million tonnes per year at time 100. Imports and commercial production were set to zero for the whole length of the simulation. The resulting behaviour for the ADESM can be seen in figure 26.

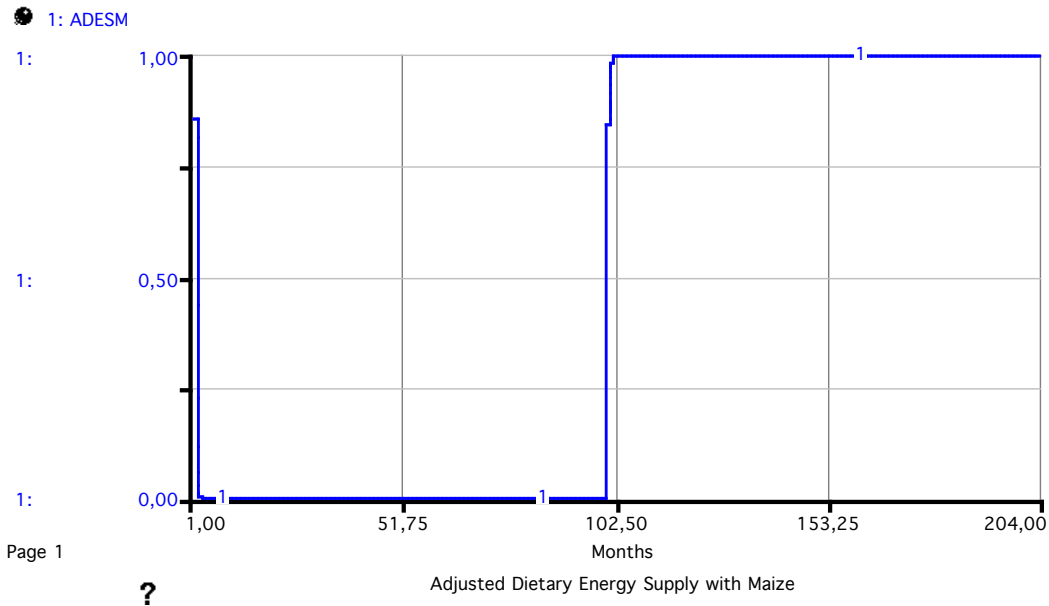


Figure 26: Behaviour of ADESM under extreme conditions

As expected, with no production coming in, the ADESM drops to zero, staying there until the step in production occurs, triggering a series of consecutive bumper harvests. With this abundant supply, consumers in all parts of the value chain are able to purchase maize as they wish, so that ADESM stays at 1 for the remainder of the simulation. This behaviour makes perfect sense and shows that the structure produces plausible results under extreme conditions.

6.2.2 Behaviour Sensitivity Test

The behaviour sensitivity test involves “determining those parameters to which the model is highly sensitive, and asking if the real system would exhibit similar high sensitivity to the corresponding parameters” (Barlas, 1996: p. 191). I perform this test by changing the parameter values upwards and downwards and evaluating the resulting change in behaviour.

While most of my inputs are well grounded in reliable sources, the highest degree of uncertainty exists concerning the different coverage and adjustment times, as they are mostly based on expert estimates. The test shows that raising the coverage times (CT) or

reducing the adjustment times (AT) in one of the value chains leads to that value chain attracting a higher share of the privately traded smallholder maize in deficit production years. This makes sense because with lower AT, the demands of the respective actors can be processed faster; and due to their faster reaction, they are able to snatch a bit more from the stock before competing buyers deplete the stock. In the case of raising the CT, we learn that a higher CT leads to stronger initial demand to refill the depleted maize storages when the new harvest becomes available: if you want to cover 5 months of 100 tons' consumption instead of 3 months, your initial demand will inevitably be 200 tons higher.

That same logic also proved to work the other way around: with a higher AT or lower CT, the respective value chain would *ceteris paribus* attract a smaller share of the available maize. However, the effects of changing the AT or CT were not very pronounced: numerical sensitivity to these parameters was very small, and changes in behaviour patterns were not observed at all. In light of this low sensitivity, it seems well sufficient to work with expert estimates for these time constants. Furthermore, the low sensitivity of the model seems plausible, as we would also not expect the real value chain to significantly change its behaviour just because a trader has doubled his coverage time or delivery speed.

Another variable that constitutes a major source of uncertainty was the Desired FRA reserves, as these were purely based on assumptions due to lack of data. However, sensitivity testing revealed that the model's historical run is very insensitive to this parameter, as the reserves switch structure represents a strong correcting feedback that makes desired reserves drop to zero in case of a domestic maize shortage. The low sensitivity due to the feedback mechanism seems plausible, as it is hard to imagine that FRA can keep significant amounts of maize locked up in their storage during a domestic maize shortage. Given the low sensitivity, it seems therefore justifiable to work with assumptions for this parameter.

As there are no other major sources of uncertainty in my model, the remainder of the behaviour sensitivity testing was about finding out which parameters have strong impact

on the model's behaviour. Production is a high-impact parameter, as was shown in section 6.2.1. Furthermore, FRA purchases have quite a strong impact on behaviour: higher FRA purchases lead to less maize being available for private buyers to purchase from smallholders. This influences the amount of maize that can be channelled into the informal value chain, which in turn has an impact on the behaviour of the ADESM (cf. section 5.2.2).

Consumer maize demand also has a strong impact on the ADESM due to the fact that the ADESM's equation directly depends on demand: the higher the demand, the lower is the ADESM for a given supply, and the other way round. Finally, the model exhibited strong sensitivity to the effect of the perceived ratio of demand for grain that is unfulfilled on the informal demand (*Effect_of_perc_ratio_on_informal_demand*). The sensitivity of the model to this parameter does make sense, as the ADESM is a function of consumption and demand. However, the theory and expert estimates underlying this graphical function seem so well justified to me (cf. section 4.7) that I deem the credibility of the source to be on a par with the relative importance of this parameter in the model.

6.2.3 Qualitative Features Analysis

This test involves specifying the major qualitative features of the expected behaviour of the model under specific test conditions, and then comparing these expectations to the actual simulation results. As the reader will have noticed, I already employed this approach in the sections describing the extreme conditions and sensitivity testing by assessing the plausibility of the results against a reasonable expectation of how the real system would behave. As the model has produced plausible behaviour in the base run and throughout the different tests, I feel confident to say that the model also successfully passes the qualitative features analysis.

6.3 Other Tests

6.3.1 Integration Error Test

This test measures the sensitivity of the simulation results to changes in the integration method and time step used in the model (Sterman, 2000: chapter 21). Cutting the DT in half or changing the integration method between Euler's Method, Runge-Kutta 2 and Runge-Kutta 4 did not have any significant impact on the simulation output. The model thus passes this test, as well.

6.3.2 Statistical Assessment of Behaviour

The highly transient behaviour of all main indicators in my model, as well as the lack of reference data for those main indicators, rule out statistical tests of behaviour validity as a viable option in my case (Barlas, 1996). Such tests are therefore not carried out and the focus is kept on structure-oriented tests.

7. Production Shock Scenarios

Having established the structure of the model, discussed its behaviour in the base run, and gained confidence in it using validation tests, the next step towards answering the research questions would be to simulate shock scenarios and analyse them using the methodological framework explained in chapter 3. However, before we can do that, it is necessary to choose and operationalize those scenarios that can then be used as the basis for the resilience analysis. This process will be illustrated in chapter 7.

As the reader knows, my resilience analysis will focus on the response of the value chain to production shocks in the form of changes in the ADESM. The choice of shocks that I will expose the model to thus hinges on two main criteria:

1. Impact:

How strong, and thereby relevant for my resilience analysis, can the impact of a given shock scenario on the ADESM expected to be?

2. Plausibility:

How plausible is the occurrence of a given shock scenario?

There is a certain trade-off between those two dimensions. On the one hand, if a scenario has only a low probability of actually happening, but potentially devastating impacts, it might still be considered worthwhile as an extreme case that shows the vulnerability of the value chain towards drastic and unexpected events. On the other hand, if a scenario unfolds a relatively weaker impact but is very likely to happen, it is important to investigate the response of the model due to the high likelihood that this scenario becomes relevant for the real system.

The different shock scenarios for the Zambian maize production will be simulated in the maize production model for Zambia built by A. Gerber. For a more detailed description of that model, see: Gerber (2015). The changing maize output simulated with that model will then constitute an external input to my value chain model.

7.1 Impact Factors on Maize Production

I started my search for relevant scenarios by thinking about which factors might conceptually constitute entry points for significant shocks in an agricultural production system. On a very conceptual level, I theorized that the following variables could be high-impact parameters for production and therefore possible entry points for a shock:

- Cultivated land
- Agricultural workforce
- Production factors, such as:
 - Capital (financial, machinery)
 - Fertilizer

- Seed
- Environmental factors, such as:
 - Exposure to water
 - Temperature
 - Exposure to sun
 - Properties of the soil

It was then necessary to clarify which of these potentially important factors actually is relevant for the specific situation of maize production in Zambia. Building on the research and model of Gerber (2015), I did this by looking at each variable mentioned in the list in turn and determining its relevance for my analysis. A parameter is considered to be relevant if it can reasonably be expected to change swiftly in a plausible shock scenario and thereby unfold a significant impact on total maize production in Zambia.

Cultivated land: This parameter has a high impact on production, as output is a function of yield and land area cultivated (Gerber, 2015). Even though changes in the cultivated land usually happen slowly as farmers expand their business over the long term, natural disasters like floods could be a plausible scenario for a sudden change in area cultivated.

Agricultural workforce: A loss of workforce in the agricultural sector would have immediate negative consequences on the production. However, since the workforce depends on the population, one would have to find a plausible scenario that would swiftly and strongly alter the course of the overall development of Zambia's population. Yet, research shows that no remotely plausible scenario would significantly alter the trajectory of Zambia's population development in a short enough time to constitute a significant shock. Even if we assume a worst-case scenario like an Ebola outbreak similar to the one in West Africa in 2014, we see that "only" around 11.000 people died in the course of these events (WHO, 2015) – which is of course very tragic, but not a number that would significantly change population dynamics for a country that is currently growing at

260.000 people per year (UNDESA, 2012). Thus, we can rule this parameter out for scenario building, despite its potentially high impact.

Capital: Since the overwhelming majority of maize (92% in 2013 (CSO Zambia, 2015; N. M. Mason, Burke, Shipekesa, & Jayne, 2011)) in Zambia is produced by smallholder farmers, who typically have rather basic means of production, financial capital and machinery are not heavily used in Zambia's maize production. Conceptually, this means that if we think of the horizontal axis in figure 27 as the input of financial and machinery capital and the vertical axis as production output, for most smallholders we would be somewhere around the red dot on the graph. This implies that even if these inputs drop to zero in case of an extreme shock, the impact would be rather small due to the overall low current level of capital employment. Hence, capital can be ruled out as well.



Figure 27: Conceptual relation capital input - smallholder production

Fertilizer: The amount of fertilizer used directly influences agricultural yield and therefore has a very strong impact on production. Although most farmers in Zambia do not use fertilizer to the point of saturation, maize production in Zambia would react very sensitive to a drop from the current level (Gerber, 2015). The most plausible scenarios for shocks affecting fertilizer use by farmers would be currency shocks (as most fertilizer is imported) or a change in the fertilizer subsidy programmes.

Seeds: Since farmers typically retain a certain share of their harvest for the upcoming seeding season, it is hard to imagine what external factor would stop them from doing that. Even though some farmers work with hybrid seeds that have higher yields in the first one or two years of use (estimates seem quite unreliable here), the worst thing that could happen if the access to new hybrid seeds dries up would be a regression towards the

normal yield after the second year. Due to this rather small expected impact on production and the unreliability of data on usage, I will exclude this factor as a potential entry point for a shock.

Exposure to water: This variable obviously has a great impact on agricultural yield: without water, there can be no plant growth. And since droughts are a recurring phenomenon in Zambia (Thurlow, Zhu, & Diao, 2009), loss of exposure to water through droughts will be a central scenario for my analysis.

Properties of the soil: The chemical properties of the soil do have a strong influence on yield. However, they usually change very slowly and thus do not lend themselves to being operationalized as a short-to-medium term shock scenario (Gerber, 2015).

Temperature: The main impact of short-term fluctuations in temperature is an increase in evapotranspiration, which is already subsumed in the “exposure to water” variable. There have been observations that higher temperature favours the occurrence of pests in other parts of the world (Leschin-Hoar, 2015), but these observations are very vague and so specifically dependent on local circumstances that they are hardly applicable to other areas. Temperature will thus be ruled out as a standalone impact factor for my shock scenarios.

Exposure to sun: Even though this factor obviously also has a strong impact on plant growth and therefore yield, there is no plausible shock scenario that would significantly alter it over the short term and I will thus rule this factor out, as well.

7.2 Description of Shock Scenarios

Following the analysis in the preceding section, we have three variables that unfold a potentially high impact on maize production in Zambia and can be expected to quickly change as part of a plausible shock scenario. These factors are:

- Cultivated land

- Exposure to water
- Fertilizer

Having established the possible entry points for production shocks, it remains to find plausible scenarios that will alter these parameters and then operationalize these scenarios for simulation in Gerber's maize production model. I will discuss the scenarios for each parameter in turn below.

Cultivated land: Economic shocks are unlikely to lead to a significant number of farmers abandoning their land, as maize is mainly produced by smallholders who are typically not very integrated in the world economy. Moreover, many of them farm not primarily for profit but to ensure sufficient subsistence consumption for themselves. The only plausible reason for a sudden change in cultivated area would then be natural disasters – and the only major natural disaster that could lead to quick and significant losses of cultivated area, which has been observed in Zambia so far, were floods (Thurlow et al., 2009).

Although floods normally occur on a local level, I also want to test the resilience towards unexpectedly strong events, as discussed in the beginning of chapter 7. Hence, I will assume stronger than usual impacts on the cultivated area through floods. When plants are partially or wholly submerged in water, oxygen intake is restricted and the plant is damaged and ultimately dies (Vartapetian & Jackson, 1997). By introducing a new effect variable that decreases the cultivated land by a certain ratio, the impacts of the hypothesized flood scenarios are – in varying degrees – moderated into Gerber's production model. The effect will range from 1,0 to 0,7, meaning that between 0% and 30% of the total cultivated area for agricultural plants (not only maize!) in Zambia is lost.

Exposure to water: Since droughts are a recurring phenomenon in Zambia and changing precipitation makes up for the majority of the variations in the plants' water household (Thurlow et al., 2009), I will parameterize the changes in exposure to water by feeding in different numbers for annual rainfall into Gerber's production model. Building on data

from Thurlow et al. (2009: p.18) and Gerber (2015), I computed a national average from their rainfall/drought scenarios for the different agro-ecological zones and refined the gradation, leading to the scale visible in figure 4:⁸

Drought Scenario	Avg. National Rainfall (mm/year)
Extreme drought	450
Severe drought	510
Moderate drought	630
Dry year	740
Normal year	879

Table 4: Drought scenarios and annual rainfall in Zambia

According to Thurlow et al. (2009), severe droughts have been observed in 3 of 5 agro-ecological zones in one year, while moderate droughts have occurred in 5 of 5 in one year. My scenarios will examine the effects of droughts in varying degrees, also going beyond what has been observed so far to test the reaction towards extreme conditions, especially as extreme weather events (i.e. droughts and floods) in Zambia might increase in the future due to climate change (Deutsches Institut für Entwicklungspolitik, 2011). The amount of precipitation directly influences the production function for maize in Gerber’s model.

Fertilizer: As laid out above, fertilizer use is a high-sensitivity parameter in Zambia’s maize production. The current situation is that most smallholders do not have the means to buy

⁸ The value for an extreme drought is defined by the lower bound of the rainfall estimates of Thurlow et al. (2009: p.18), while the data for a normal year is derived from the value for rainfall assumed in the base runs of Gerber’s production model. Severe and moderate drought were defined for the different agro-ecological zones in Zambia by Thurlow et al. (2009), and I took a weighted average to transform them into national averages. The category of “dry year” was included to close the gap between a moderate drought and a normal year.

as much fertilizer as they would like to, so the government heavily invests in fertilizer subsidies through the Fertilizer Support Program (FSP) (World Bank, 2010).

Since natural gas is in good supply these days due to shale gas exploitation, and real global prices for potassium and phosphate products have been very stable in recent years, even steadily trending downwards since 2011 (World Bank, 2015a), it is unlikely that global market prices for the most important fertilizer input factors suddenly increase in the near future. However, since the vast majority of fertilizer has been imported to Zambia in recent years (FAO, 2015a), and strong currency fluctuations have been observed for the Zambian Kwacha in the last years (World Bank, 2015b), it seems well possible that a currency shock suddenly increases fertilizer prices for Zambian farmers. Due to the strong reliance on fertilizer subsidies, another possible scenario leading to a shock in farmer's access to fertilizer would be the withdrawal of funds from the FSP in the course of a budget crisis.

While the fertilizer subsidy shock scenarios can easily be parameterized for Gerber's model by just changing the sum of money that goes into the subsidy programme, operationalizing the impact of currency shocks on fertilizer availability is more difficult.

Fertilizer is, like most commodities, internationally traded in US Dollars (Dumas, 2015) – so that the domestic price in Zambia for imported fertilizer depends on the exchange rate of the Zambian Kwacha against the US Dollar. If the value of the Kwacha against the Dollar falls by e.g. 50%, imported fertilizer effectively becomes, *ceteris paribus*, twice as expensive. However, since Zambia has currently inactive domestic fertilizer production facilities that are supposed to have a maximum production capacity of up to 60.000 tons/year (Nitrogen Chemicals of Zambia Limited, 2015), a dynamic response can be expected in the case of a strong price rise in the form of re-initiating domestic fertilizer production. I incorporated this effect into my scenario by assuming that, with a delay of one planting season, domestic production would be re-initiated and gradually rise towards the maximum capacity over the years if the unfavourable exchange rate persists. Assuming a steady demand for fertilizer, the ratio of imported production would then gradually decline

towards a minimum of 0,73. The resulting variable “*Effect of currency shocks on fertilizer price*” that will be fed into Gerber’s production model will therefore be computed in the following way:

$$\text{Currency Effect} = \frac{\text{New exchange rate value}}{\text{Initial exchange rate value}} * \text{Ratio imported fertilizer}$$

As far as historically observed values for changes in the exchange rate are concerned, we can see that as short back as from 2008-2009, the Kwacha’s value against the US Dollar fell by 35% in a year’s time (World Bank, 2015b). I will thus test a scenario repeating this increase, as well as a slightly stronger scenario where the Kwacha falls by 50%.

8. Resilience and Scenario Analysis

In this chapter, I will present the results of the different scenario simulation runs and analyse them in terms of the resilience framework laid out in chapter 3. Furthermore, I will explore the impact of the model structure on the resilience properties exhibited. The results will enable me to provide answers to the central research question.

8.1 Changes in Scenario Run Models compared to Base Run Model

In order to reflect my assumption for the scenarios that FRA will pursue a policy of buying half of the yearly smallholder surplus production, rather than entering new external data for FRA purchases in every other simulation I found it easier to build a structure that endogenously computes the value for the FRA purchases by multiplying the yearly smallholder surplus production by 0,5. To make this structure work, I furthermore had to add a logical function to the FRA purchase flow and the non-FRA smallholder purchase switch structure that makes them choose the endogenously computed value instead of the

external historic data from 2015 (month 133) on. Apart from that, the model structure is the same as presented in chapter 4 for the base run.

8.2 Overview of Simulation Results for the Different Scenarios

Following the methodology laid out in chapter 3, I will measure the resilience of the value chain in terms of the integral between the curves for the ADESM in the base run and the ADESM in the respective shock scenario runs. The maximal impact of a shock would thus be that the ADESM goes to zero for all the six years, or 72 months, simulated into the future. This would lead to an integral of 60 between the base run's ADESM and the shocked run's ADESM. The minimum difference is of course 0 when there are no adverse effects on the ADESM in the scenario run. Using this range as a yardstick, we can thus analyse the resilience of the value chain towards the different production shock scenarios. The results are summarized in table 5.

Scenario	Description of shock	ADESM integral final value
1	Permanent Increase in Kwacha Value Towards US Dollar by 35%	5,57
2	Permanent Increase Kwacha Value Towards US Dollar by 50%	8,49
3	Flood Loss of Cultivated Area by 10% in 2015	0,18
4	Flood Loss of Cultivated Area by 20% in 2015	0,45
5	Flood Loss of Cultivated Area by 30% in 2015	1,44
6	Flood Loss of Cultivated Area by 20% in two consecutive years (2015-16)	1,95
7	Extreme 3-year Drought (2015-17)	20,08
8	Extreme 2-year Drought (2015-16)	12,44
9	Extreme 1-year Drought (2015)	6,17

10	Severe 2-year Drought (2015-16)	10,33
11	Severe 1-year Drought (2015)	5,02
12	Moderate 2-year Drought (2015-16)	6,71
13	Moderate 1-year Drought (2015)	2,75
14	Extreme followed by Severe Drought (2015-16)	11,41
15	Steady Fertilizer Subsidies of 1500 Kwacha/Person/Year	0
16	Fertilizer Subsidies Permanently Cut in Half to 750 Kwacha per Person and Year	4,64
17	Fertilizer Subsidies Permanently Abandoned	13,88
18	Flood Loss of Cultivated Area by 20% and Zero Subsidies in 2015, followed by Subsidies Cut-in-Half to 750 Kwacha/Person/Year in 2016	3,96
19	Flood Loss of Cultivated Area by 20% in 2015 and 2017, as well as Permanently Abandoned Fertilizer Subsidies	18,48
20	Severe Droughts in 2015 and 2017 and Extreme Drought in 2016, as well as Reduced Fertilizer Subsidies in 2015 and 2018 (750 Kwacha/Person/Year) and No Fertilizer Subsidies in 2016-17	19,77
21	Severe Droughts in 2015 and 2017 and Extreme Drought in 2016, as well as Permanently Abandoned Fertilizer Subsidies	26,31
22	Extreme Droughts in 3 consecutive years (2015-17), as well as Permanently Abandoned Fertilizer Subsidies	27,41

Table 5: Overview of scenarios and final ADESM integral value

Scenarios 1-17 are “single-shock scenarios”, where only one type of shock hits the maize production system in Zambia, such as droughts or currency shocks. Scenarios 18-22 are “combined scenarios”, where the production system is exposed to simultaneous or consecutive shocks of two types. Scenario 15 is untypical insofar it does not produce a

shock. A detailed overview of the changes in the ADESM for each scenario featuring the graphical simulation output can be found in appendix B.

8.3 Analysis of Scenario Simulation Results under the Resilience Framework

Using the final value of the integral between the scenario and base run ADESM as a metric, we can evaluate the relative resilience of the value chain towards the different production shock scenarios. In order to keep the analysis as concise and informative as possible, I will group the scenarios according to the nature of the shock scenario and evaluate the resilience of the value chain to the different types of shock scenarios. In the course of this analysis, especially in sections 8.3.3 and 8.3.4, I will also explain the dynamics of the effects of production shocks on the resilience metrics in greater detail.

8.3.1 Exchange Rate Shock Scenarios (No. 1-2)

While currency shocks do have a significant impact on the ADESM, their accumulated effect is less pronounced in the medium to long term compared to the fertilizer subsidy and drought scenarios. In terms of our methodological framework, the initial vulnerability is not very high, but the permanence of the change undermines the adaptive capacity, so that in the third year, the maize buffer stocks (i.e. stocks maize stocks that are carried over from one year to the next to act as a security buffer in case of a shock) are depleted and the structural maize (production to demand) deficit that is growing bigger over the years, cannot be compensated any more. The ADESM therefore then breaks down to zero in 2017 (months 156 – 167) and the integral surges up.

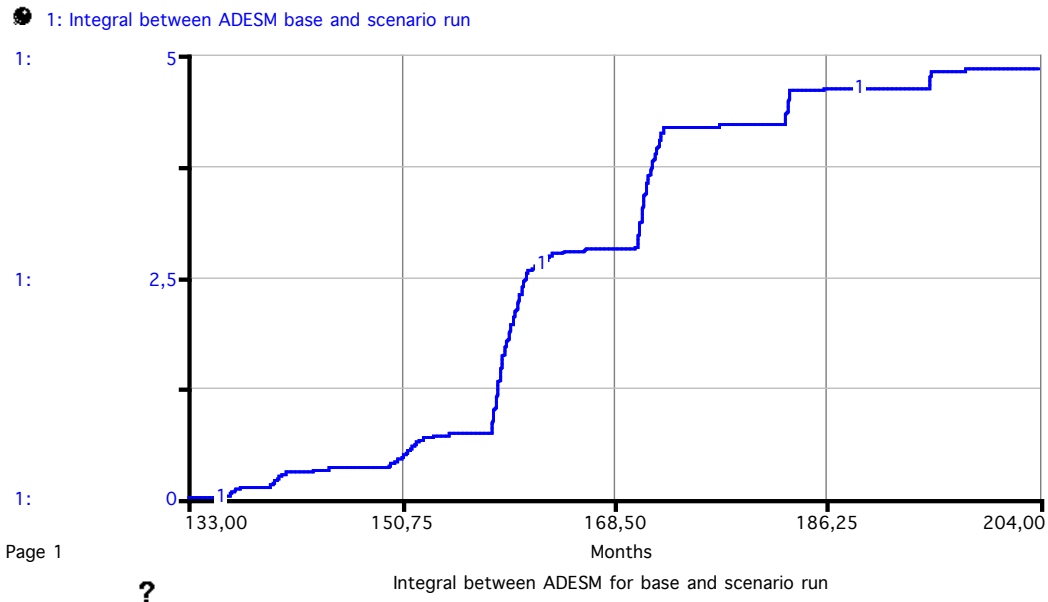


Figure 28: Development of ADESM Integral for scenario 1

However, due to the dynamic market response I assume (see chapter 7.2), the producers compensate for the more expensive fertilizer imports by raising domestic production. This leads to decreasing marginal yearly impacts of the changed exchange rate value on the ADESM, as can be seen by the decreasing growth of the integral. The adaptive capacity thus becomes stronger again over time.

8.3.2 Flood Loss Scenarios (No. 3-6)

The maize value chain in Zambia is quite resilient towards flood losses of cultivated area, as the relatively small maximal value of 1,88 for the impact of the flood scenarios shows. As can be seen by comparing scenarios 4 (one-year flood) and 6 (two-year flood), the adverse effects on the food supply rise exponentially when floods occur in two consecutive years: one year with 20% area loss has an effect of only 0,45, while the same event occurring in two consecutive years has an effect of 1,95. The impact is thus more than four times as high when the same flood loss shock is repeated in a consecutive year.

To investigate the reasons for this increasing impact, it we need to look at the change of maize supply over the flood years (2015-16). Maize can be supplied to consumers either

from fresh production of the current year or from carryover stocks that were accumulated over the last years. Comparing the graphs for SC 6 and the base run in figure 29, we can see that the difference between yearly maize production in both actually becomes smaller in the second shock year of 2016. Changes in the production for the current year can therefore not explain the increasing impact.

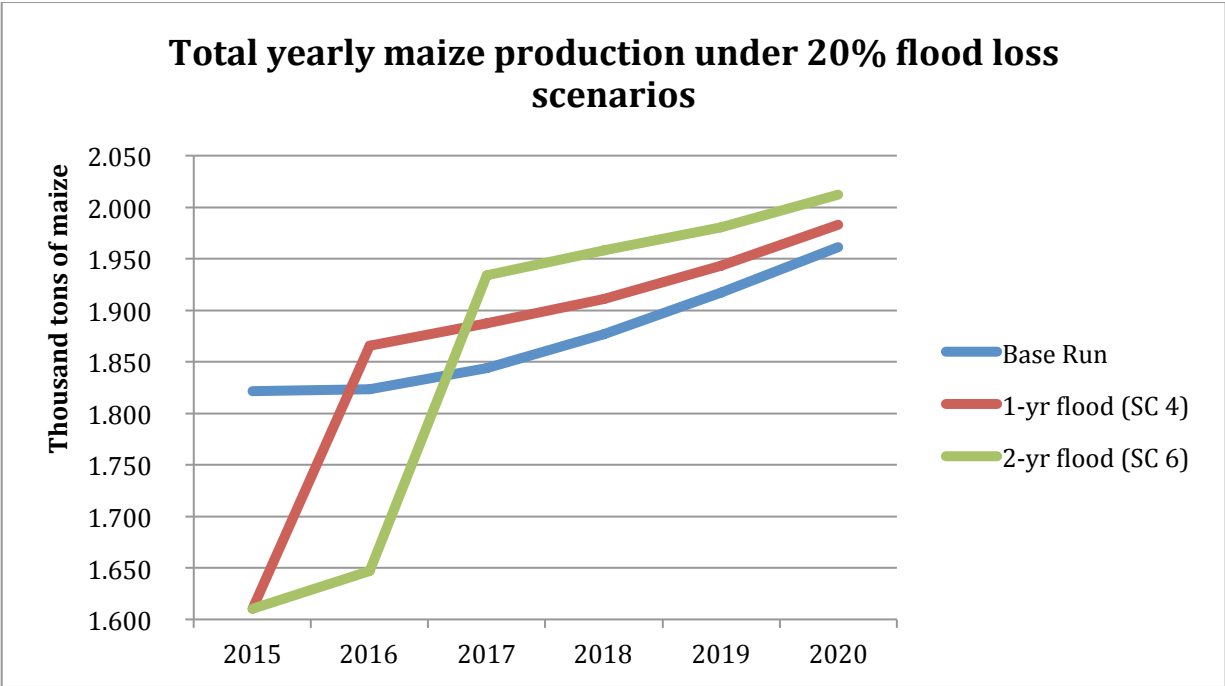


Figure 29: Total yearly maize production under 20% flood loss scenarios

The answer can be found in the difference of the total maize that is stored throughout the value chain: for this parameter, the difference between scenario 6 and the base run becomes much bigger in 2016, as buffer stocks had to be used up in order to maintain a sufficient supply in 2015 (see figure 30).

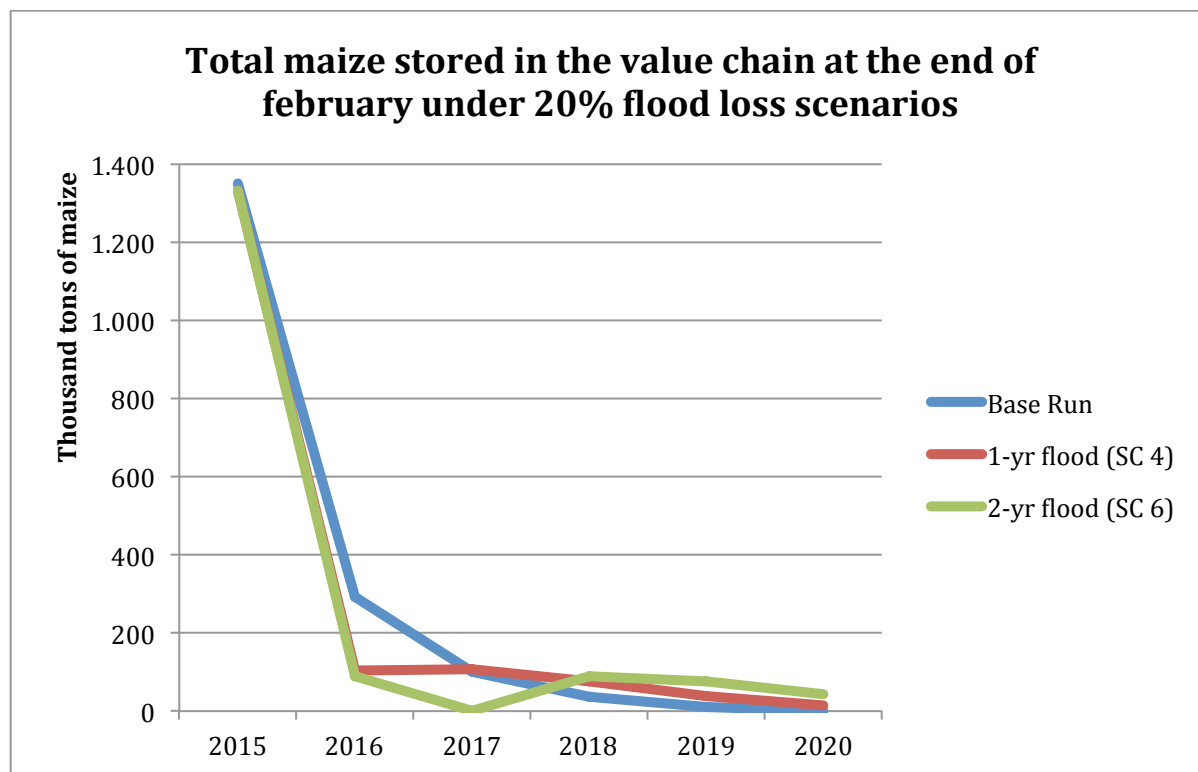


Figure 30: Total maize stored in the value chain under 20% flood loss scenarios

Since 2016 is a year with just enough production to prevent the ADESM from dropping to zero, stored maize stocks are consumed and reach virtually zero at the beginning of the 2017 marketing season. 2017, however, is a year with an even worse supply-to-demand ratio where buffer stocks would be needed even more. As these are now depleted, the low production can – other than in the base run and scenario 4, which feature enough buffer stocks, not be offset and the ADESM drops to zero, as can be seen in figure 31. This drop of course leads to a strong increase in the integral between the scenario and base run ADESM (cf. figure 32), and therefore ultimately explains the big difference between two-year and one-year flood shock scenarios. Since scenario 6 features higher production than the base run in 2017-2020 due to a rebound effect in production, it's ADESM actually performs better than the base run in 2018-2020 (cf. figure 31).

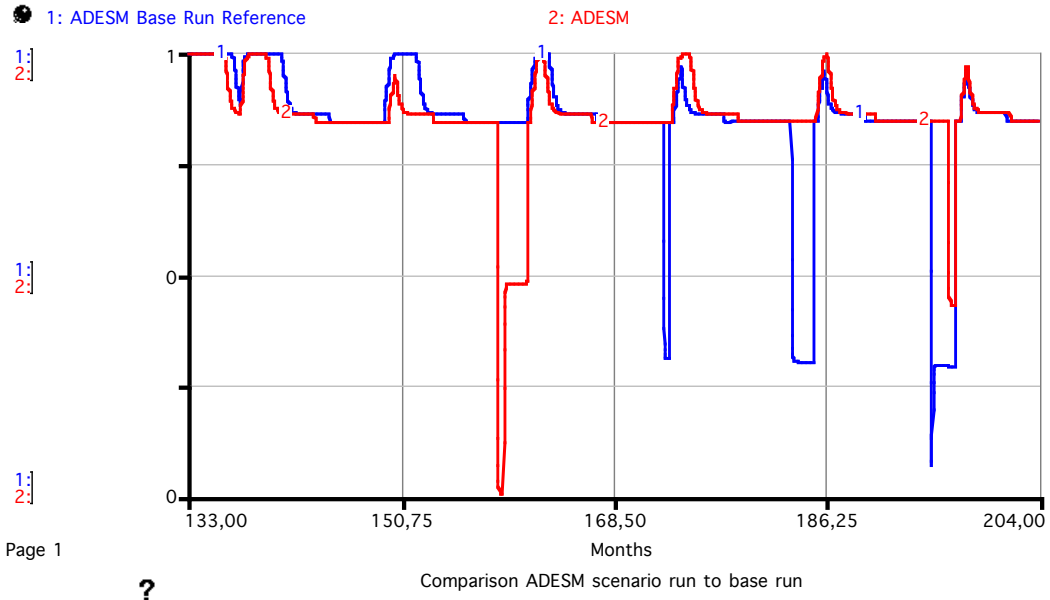


Figure 31: ADESM comparison scenario to base run for scenario 6

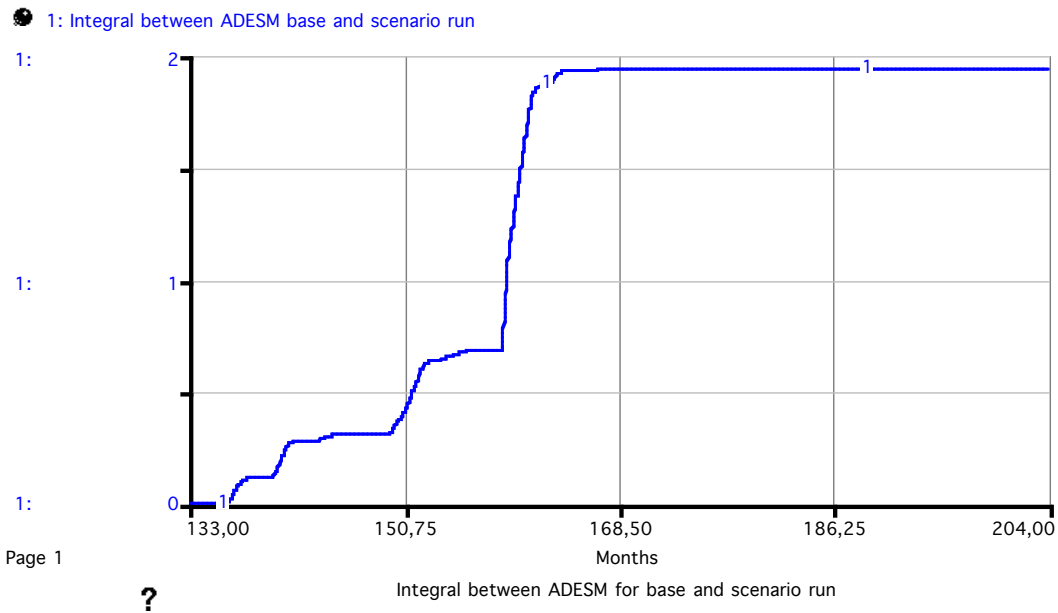


Figure 32: ADESM Integral for scenario 6

The behaviour observed leads to an interesting conclusion: the initial vulnerability of the value chain to the flood-induced area losses is not that high, but there is a certain threshold of time with consecutive shocks, after which the system becomes very vulnerable to any

further perturbation in the production due to the depletion of buffer stocks. We can thus attribute the resilience properties towards production shocks to two main factors: the change in yearly production itself, and the ability to buffer the effects of production shocks through carryover maize stocks from the preceding years.

The behaviour observed and described in the last paragraphs can be generalized across all the scenarios simulated: while differences between the base run and scenario ADESM normally are greatest in the years of the actual shock events, there usually is a lasting adverse effect buffer maize stocks. Looking at these stocks and the current production is the key to understanding the development of our resilience indicators.

The reader should note that in some scenarios, production lags behind in the years following the shock by a small margin, e.g. the drought scenarios; while in other scenarios yearly production actually overtakes the base run reference production due to a compensation response. The latter is the case for the flood loss scenarios. However, these responses are caused by dynamics in the production sector, are thus external and I therefore will not expand on this topic.

While there is not much that actors in the value chain can do to change the production output of maize, the finding about the buffer stocks is interesting in terms of my research question of how resilience properties can be enhanced. If it was possible to accumulate higher buffer stocks in the value chain, the impact of shock events could be mitigated and the resilience properties thereby ameliorated. This will be discussed in more detail in section 9.2.

8.3.3 Drought Scenarios (No. 7 – 14)

Drought scenarios have the highest impact of all the single-shock scenarios. In the case of three consecutive extreme droughts in scenario 7, the final integral value of 20,08 shows a substantial impact, which amounts to more than a third of the integral value that a complete loss of supply would cause. We can thus conclude that the value chain is very

vulnerable to drought scenarios, mainly because the adverse effects of droughts on maize production are very substantial compared to other scenarios.

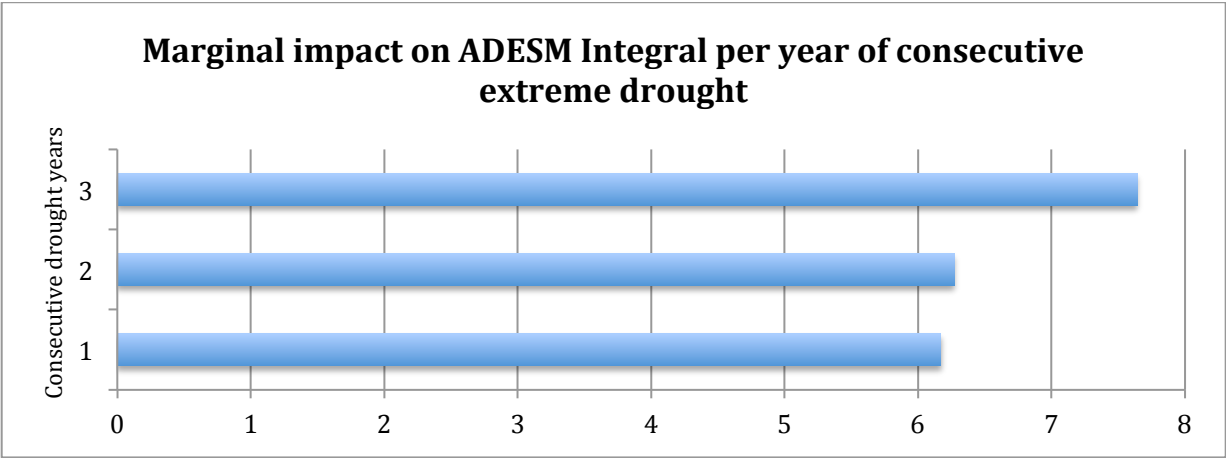


Figure 33: Marginal yearly impact of drought scenario on ADESM integral

Just like the flood scenarios, drought scenarios show an increasing marginal yearly impact on our resilience indicator. This is due to the same reasons as discussed for the flood scenarios, namely the progressively depleted buffer stocks. However, since the overall loss in yearly production is much higher in these scenarios, the effect of change in current production is so great that the effect of the buffer stock development is relatively less important. This can be seen by the small relative growth in marginal impact compared to the flood loss scenarios, displayed in figure 33.

8.3.4 Fertilizer Subsidy Scenarios (No. 15 -17)

The fertilizer subsidy shock scenarios are different from the other classes of shocks, as the system faces a permanent change without a built-in compensation response like in the exchange rate shock scenarios. Subsidies are cut in half (scenario 16), or abandoned completely (scenario 17) in 2015 and then stay that way all through to 2020. This leads to production constantly being around 6,5% lower every year compared to the base run in scenario 16 and around 19,5% lower in scenario 17 throughout all six years. Looking at the graphs for scenario 16, we can see how this translates into changing our resilience indicators.

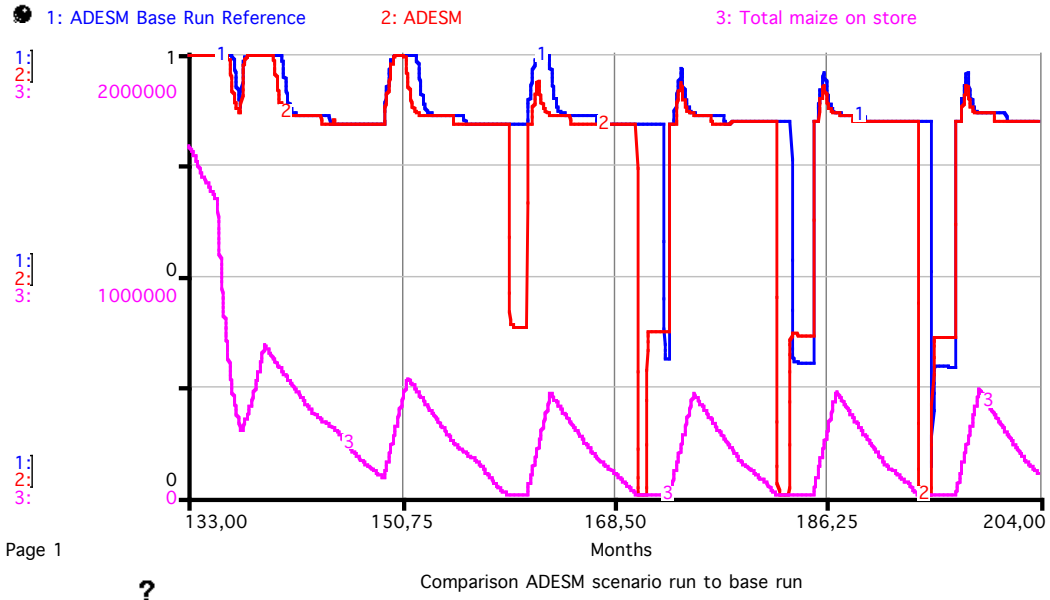


Figure 34: Comparison of ADESM and maize stocks for scenario 16

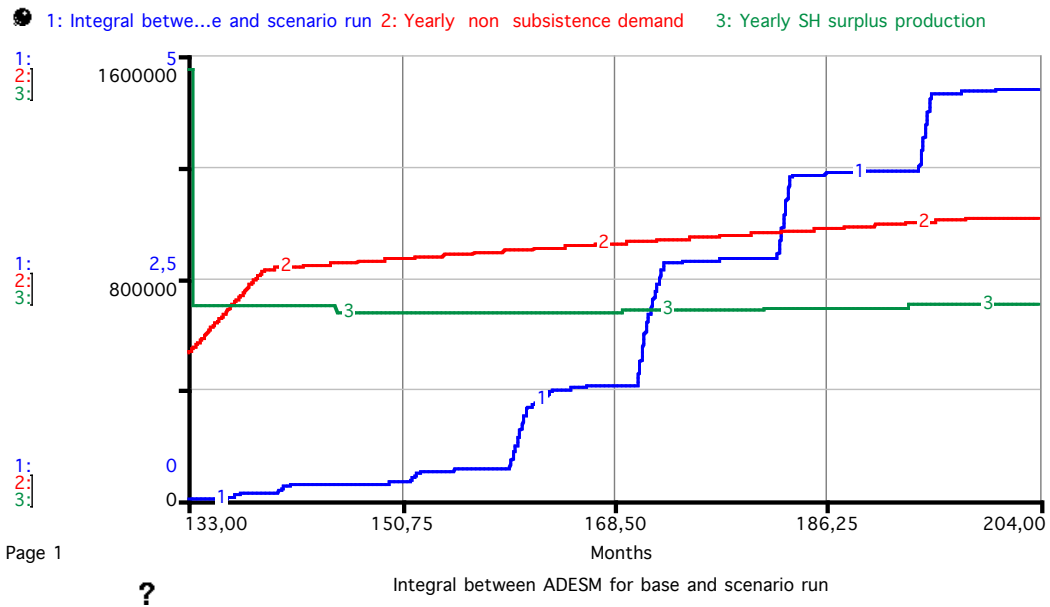


Figure 35: Development of ADESM Integral against yearly demand and production for scenario 16

The logic behind the behaviour of the resilience indicators is similar to the one explained in section 8.3.2. There is only a relatively small excess original demand⁹ (i.e. demand exceeding production) in 2015, so that the production deficit can be buffered by the consumption of carryover stocks. The size of the carryover stocks is represented by the local minima of the purple line in figure 34. In 2016, however, the difference between production and original demand rises and the buffer stocks are now lower than the year before. The growing gap in 2016 cannot be redeemed by consuming the already reduced buffer stocks and the ADESM drops to zero later in the 2016-17 marketing year. The permanently low production and the rising population lead to an ever-growing gap in demand vs. production that does not allow carryover stocks to be built up. This leads to the breakdowns in ADESM becoming progressively bigger in every consecutive year's lean season. The only reason why the growth of the integral slows down in 2019-20 (months 181-204) is that the base run also performs worse over time.

While the initial vulnerability is quite low, as indicated by the shallow initial growth of the integral, due to the permanence of the effect, the adaptive capacity of the system is undermined as buffer stocks are depleted. The shock effects therefore accumulate to a significant level in the long run. If the shocks were only to occur in one or two consecutive years, the impact on the ADESM would be comparatively small, probably comparable to what we have seen for the flood loss scenarios. I therefore conclude that resilience of the value chain towards shocks in the fertilizer subsidies is relatively high compared to other shock types when they feature the same number of impact years.

Before moving on to discuss the combined scenarios, I would like to draw the reader's attention to a phenomenon that is important in understanding the resilience analysis. There is effectively a "threshold" behaviour for the ADESM in my model: since there are only effectively two compensation mechanisms in terms of demand adjustment when maize becomes scarce (eating less per day and changing to other carbohydrate sources),

⁹ „Original demand“ refers to the demand before it is adjusted for dynamic consumer responses to scarcity, as explained in chapters 4.7 and 4.8

the ADESM either stays at 0,84 where both mechanisms are at play and the consumption is sufficiently reduced to not exceed supply – or it collapses to zero very quickly as all maize stores in the value chain are depleted. Whenever this sometimes fine threshold is crossed and the ADESM thus falls to zero in the scenario run, but just manages to stay at around 0,84 in the base run, the integral surges up.

8.3.5 Combined Scenarios (No. 18-22)

The combined scenarios have – except for scenario 18 – a very strong impact on the ADESM. The impact of the combined scenarios reflects what we have found out about the resilience of the value chain to the different single-shock scenarios: the lower the resilience of the value chain is to the single shocks that make up the combined scenario, the greater is the impact of the combined scenario as well. The underlying dynamics of the translation of production shocks to changes in the ADESM are essentially the same as described in sections 8.3.1 through 8.3.4 and I will thus not go into detail about them again.

An interesting observation is that the combined scenarios have a lower impact on the ADESM than the sum of the two single-shock scenarios. For example, the 3-year extreme drought leads to a final value of the integral of 20,08 and the abandonment of fertilizer subsidies to an integral of 13,88. Yet, the impact of the combined shock scenario 22, featuring both of these developments, does not amount to an integral value of 33,96, but instead only 27,41. The reason for this is that the production sector shows a decreasing marginal impact on yearly maize production when shocks are added up. In graphical terms, the relationship would conceptually look like the graph in figure 36, where the

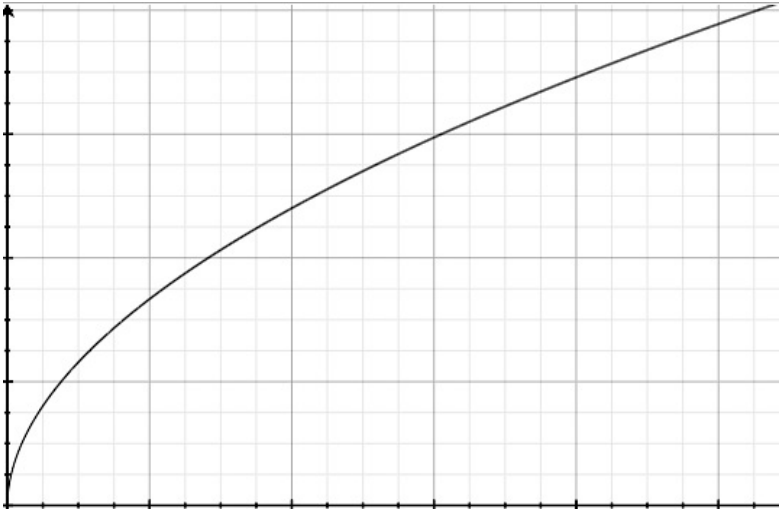


Figure 36: Relation between strength of shock and impact on ADESM

horizontal axis would represent the rising strength of the shock by adding up different types of shocks, and the vertical axis would embody the impact on the ADESM in the model.

8.4 Conclusions Resilience and Scenario Analysis

To close this part of my analysis, I want to sum up the most central findings from this chapter. These findings also provide a preliminary answer to my central research question about the resilience properties of the value chain:

- The value chain is **quite resilient** towards **flood events** causing loss of cultivated area, as well as towards **exchange rate shocks**.
- The value chain is **moderately resilient** towards **fertilizer subsidy shocks**. The moderately strong effect of these scenarios is mostly attributable to the permanence of the change. The effect can be expected to be rather small when assuming that the shock only lasts one or two seasons, as the initial vulnerability of the value chain towards fertilizer subsidy shocks was shown to be low.
- The value chain is **vulnerable** towards a **prolonged drought**. While a drought lasting only one year still has only limited impact and its effects on the ADESM can be mitigated through the consumption of carryover stocks, already a second consecutive medium to extreme drought year depletes the buffer stocks and unfolds increasingly strong impacts on the maize supply.
- Even though there is a decreasing impact on the ADESM when combining two shocks, the value chain is generally very vulnerable towards a combination of shocks hitting it simultaneously or consecutively.
- In general, the resilience of the value chain towards a one-time shock (only occurring in one production season) is quite good and it exhibits a low initial vulnerability. However, as soon as it is faced with consecutive shocks, the adaptive capacity quickly wears off as buffer stocks are soon depleted after one or maximum two years, and the impacts on the ADESM become very significant.

- There are two main determinants for the effect that a shock has on the ADESM in the value chain: the change in the current year's production, and the availability of carryover stocks that can act as a buffer. The policy analysis in the next chapter will therefore focus on how buffer stocks can be used to enhance the resilience properties of the value chain.

8.5 Impacts of Model Structure and Feedbacks on Resilience Properties

Trying to keep the analysis of the different resilience responses of the model as concise as possible, I focused on the most important impact factors that actually change in between the scenarios and therefore explain the differences observed. These are, as we learned in the preceding sections, maize production and buffer stocks. The model structure itself did not change across the scenarios, wherefore I did not explicitly mention its effects on the ADESM in chapters 8.2 to 8.4. However, even though we found out over the course of my analysis that the resilience properties of the value chain concerning production shocks are to a large degree determined by changes in external input; the feedback structure of the value chain model significantly influences the results of the resilience analysis as well. How exactly this relationship between structure and behaviour looks like will be discussed in this section.

Since the ADESM is computed using demand and supply, the demand adjustment loops naturally have a strong influence on the ADESM's development. Remember that there are two demand adjustment feedback loops: the reduction of daily consumption by customers in the informal value chain, as well as the spill-over of demand from the informal to formal value chain, including a certain share of consumers changing to other crops (cf. section 4.2.2). To see the effect of these loops on the ADESM, I simulated scenario 16 in three different instances:

- 1) Structure as usual
- 2) No demand adjustment in relation to availability in the informal value chain
- 3) No spill over of demand to the formal value chain or other crops

4) Neither demand adjustment nor demand spill over

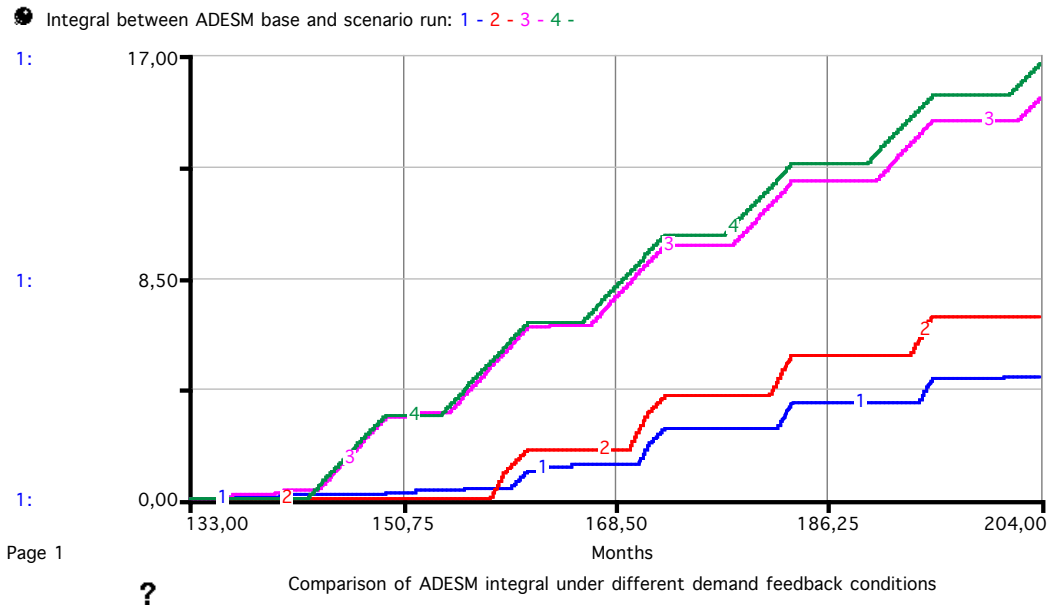


Figure 37: Comparison of ADESM integral under different demand feedback conditions for scenario 16

Looking at the comparison of the different ADESM integrals (between the base run and the respective simulated conditions of scenario 16) in figure 37, we see that the differences are very significant. Taking away the demand adjustment (2) raises the integral by 57%, indicating that this compensation mechanism is vital for the value chain's capacity to deal with production shocks.

Even stronger was the impact of switching off the demand spill-over loop (3), which led the ADESM integral to rise by 232% compared to the "structure as usual" scenario - showing the even higher importance of this coping behaviour for the value chain's resilience properties. Finally, I simulated a condition where both feedbacks were inactive (4), which produced a rise in the ADESM integral by 275%, confirming the importance of each loop.

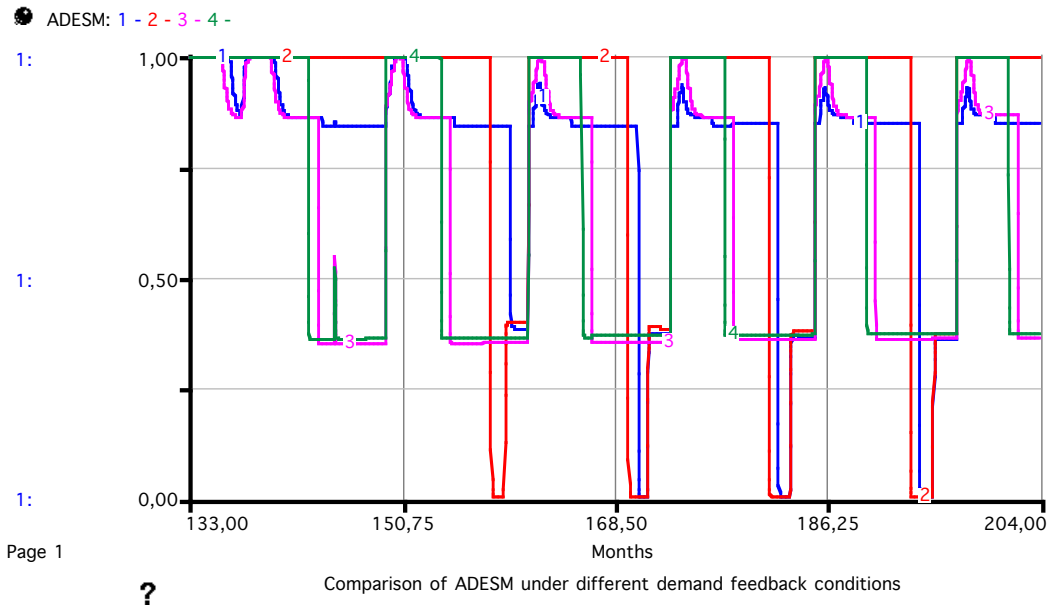


Figure 38: Comparison of ADESM under different demand feedback conditions for scenario 16

Studying the ADESM's behaviour under the different conditions in figure 38 indicates what the reasons behind the impacts observed were. Without the demand adjustment (2), the informal consumers did not adapt their daily consumption downwards in times of scarcity, leading to an ADESM value of 1 instead of 0,84 in 2015 (months 133-144). However, they thereby depleted their buffers stocks and were more vulnerable to the structural maize deficit emerging in 2016 (months 145-156), where consumption therefore collapsed earlier and stronger around month 157 due to the higher daily consumption and the lack of buffer stocks. While the buffer stocks are also depleted in the "structure as usual" instance (1) by 2017 (months 157-168) and the ADESM in this run then also collapses to zero; due to the higher consumption earlier in the year, the "no demand adjustment" version's (2) ADESM collapses earlier in the year as supplies are depleted faster. This keeps happening every year for the remainder of the simulation.

Comparing the ADESM graphs for the "no spill over" version of scenario 16 (3) with the base scenario (1) in figure 38, we see that graph 3 goes down to a value around 0,35 soon after each year's harvest. This indicates the state where informal consumers have nothing more to eat and simply starve or consume other crops, while consumers in the formal value

chain have sufficient supply (which is responsible for the remaining 0,35), as they do not have to share their supplies with informal consumers later in the marketing year. The combined version featuring neither of the two feedback loops (4) then simply combines the initial higher consumption after the harvest and the ensuing earlier breakdown for informal consumer with the steady floor value of 0,35 – leading to an even higher integral.

However, besides the consumption adjustment loops, there are three switch feedback structures whose influence on the resilience properties I want to examine next. Again, I simulated four different structural instances for scenario 16:

- 1) Structure as usual
- 2) Commercial farmers export switch turned off (cf. section 4.6.4)
- 3) FRA reserves switch turned off (cf. section 4.6.2)
- 4) Smallholder non-FRA purchases switch turned off (cf. section 4.6.3)

Turning these switches off in turn revealed the following impact on the ADESM integral between the base run and the different versions of scenario 16, visible in figure 39:

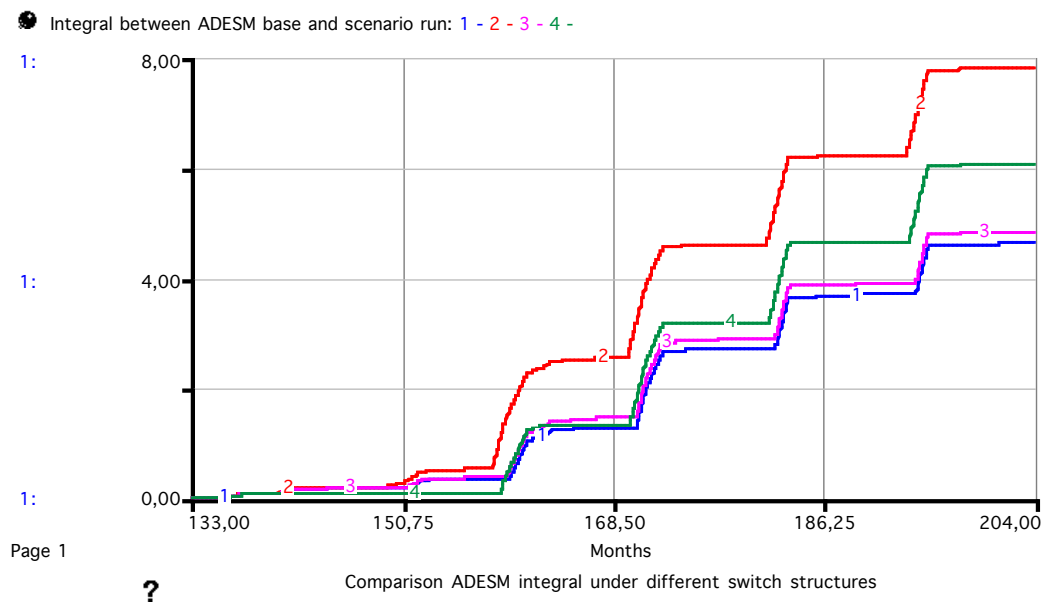


Figure 39: Comparison ADESM Integral under different switch structures

In figure 39, we see that turning the commercial farmer export switch off (2) has the greatest impact on the integral, as it rises nearly by 70% compared to the base scenario. Normally, the switch represents the export bans that the government introduces in years of structural maize deficits. With this switch turned off, commercial farmers prefer to export their maize and the domestic market loses even more supply, driving down the ADESM.

Turning the FRA reserves switch off (3) unfolds only a small adverse impact, as seen by the small rise in the ADESM integral in figure 39. Turning this switch off leads to FRA keeping strategic maize reserves even in years with structural deficits. This takes maize out of the market, worsening the supply situation. However, as FRA's storages are relatively small in scenario 16, the effect is not that pronounced – it would be stronger with greater FRA reserves.

Instance (4) encompassed turning off the non-FRA smallholder sales switch, meaning that smallholders now sell according to “first come, first serve” and do not show the strategic behaviour of reserving maize for selling it to FRA later in the marketing year. Although FRA's policies are often ineffective, especially in surplus years (cf. section 5.2.2), in scenario 16 they have a favourable effect on the ADESM (cf. figure 39): FRA's purchases lock up maize in the formal value chain and thus deplete the supply of grain for the informal value chain. Consumers in the informal value chain therefore reduce their demand earlier on and switch to other crops sooner, so that the overall demand goes down – which has a positive effect on the ADESM. Therefore, the integral rises when this switch is turned off.

Apart from the impact of the feedback structures on the resilience properties discussed so far, also the supply chain structure with its information feedback has an important effect on the ADESM. As discussed in chapter 5.2.2, these structures determine how much of the smallholder maize available for private purchase is distributed into the informal vs. formal value chain. As just explained in the last paragraph, this distribution affects the ADESM and therefore the resilience properties.

Another feature of the structure that has effects on the ADESM are the losses: the duration of storage and the distribution between the different actors (esp. FRA) determines the amount of losses throughout the value chain – thereby affecting supply and ultimately the ADESM. And of course, in times of FRA surplus purchases, FRA’s decision on how much to export has a large impact on the creation of buffer stocks and thus the resilience of the value chain. I will come back to this in chapter 9.

Summing up, we can conclude that even though the resilience properties of the value chain are determined to a great degree by exogenous factors such as the changes in production, the feedback structure of the model significantly affects how resilient the value chain is to a given shock. We saw that the two consumption adjustment loops had the strongest impact due to their direct influence on the ADESM. Moreover, the non-FRA smallholder sales switch and the information feedback structure of the informal and formal value chain (cf. section 5.2.2) were shown to affect the distribution of maize between the two value chains. And since consumers respond differently in each value chain due to the two consumption adjustment loops, this distribution in turn affects the ADESM and thus the resilience properties. Since also the other features of the model structure, such as export decisions and the FRA reserves switch, as well as the loss outflows have an, albeit smaller, impact on the resilience metrics; we can conclude that the fine-grained modelling of the value chain’s (feedback) structure was crucial in determining the resilience of the value chain towards the different production shocks.

9. Policy Analysis

After having evaluated the resilience properties of the value chain in chapter 8, in the following section, I want to find answers to the question how they can be improved. Building on the results from chapter 8 showing that buffer maize stocks play a crucial role

in determining the resilience of the value chain towards production shocks, I designed policy interventions that aim to promote the creation of those stocks. I will discuss the policies and how they change the simulation results under different scenarios in the next two sections, closing the chapter with an evaluation of the policies' feasibility for implementation.

9.1 Policies Under Base Run Assumptions

The policy I want to test is rather straightforward and relies on existing structures that are already well established. Namely, I want to see what happened if FRA would try to fulfil its original mandate: increasing food security for Zambians by buying and keeping strategic maize reserves as buffer stocks. To test the effect of such storage policies under different circumstances, I will simulate them in a low-impact scenario with permanent change, as well as a high-impact scenario featuring a shock of limited duration.

First, I will look at **scenario 8**, which encompasses an extreme drought in two consecutive years that leads to a final ADESM integral value of 12,44 in the original scenario run. Since the base run encompasses a structural maize deficit for the next years, it is difficult to accumulate carryover stocks without hurting the supply for the current year too much. As a compromise, I set the policy so that FRA would accumulate stocks only the in first shock year of 2015, where the structural deficit is still smaller than in 2016. By choosing a value for the desired reserves that is just high enough so that the compensation mechanisms on the consumption side prevent the ADESM from going to zero in 2015 in spite of the lower supply, and then releasing this maize in 2016 – a year with an exacerbated structural maize deficit – the overall performance of the ADESM could be enhanced. The final integral in that case would only be 11,3.

The logic behind the relative success of this policy is that the marginal positive impact of extra maize supply in 2016 is higher than in 2015: extra maize that would “only” have helped to keep the ADESM at a value of 1 instead of 0,84 for longer in 2015, helps to stabilize it at 0,84 instead of going to zero in 2016.

However, the success of this policy depends on very fine-tuned management of the maize stocks by FRA and it is questionable if they would be able to determine which is just the right amount of maize to store and release. Moreover, it would probably take some kind of anticipation that another shock is to follow in the next year to execute the policy in the way described. Finally, I deem the political feasibility of this policy to be quite low, as withholding maize in times of supply shortage seems like a policy that would quickly falter to domestic political pressure to release the maize right now.

Next, I want to test if similar results are obtained in a different scenario setting. Hence, I will look at **scenario 16**, which features the permanent reduction of fertilizer subsidies per capita by 50%, leading to a final integral value of 4,64 in the original scenario run. Different to our findings for scenario 8, the policy of storing maize in 2015 and then releasing it later on does not have any significant positive effect on the overall development of the ADESM in scenario 16. This is because due to the permanence of the change, there is no central crisis year (like 2016 in the case of scenario 8), and the marginal impact of maize on the ADESM is more or less the same throughout all years. Therefore, transferring maize from one year to another does not significantly raise the ADESM.

The simulation results confirm that it is hard to implement a storage policy with significant positive effects on maize supply in an environment of constant structural maize deficits. The best effect one can hope to achieve with such a policy is to transfer maize from a bad year to an even worse year, where its marginal positive impact on supply security would be slightly higher. However, this policy would require very fine-grained management and is likely to falter to political pressures. In any case, it does not significantly enhance the resilience properties, as the underlying problem of a structural maize deficit cannot be redeemed.

9.2 Policies Under Changed Scenario Assumptions

Having thus established that policies relying on storing domestically produced maize are not promising in an environment of constant structural maize deficits, I want to explore the

effects of storage policies in an environment with occasional bumper harvests – which, as we know from historical data, do regularly occur in Zambia (cf. appendix C.1).

The scenario I will use to investigate the effects of the policy is a combination of the base run, a high production scenario and scenario 8. The distribution of maize production for the scenario (in metric tons) over the years can be seen in table 6:

Year	Smallholder surplus	Commercial farmers	Subsistence Production	Data taken from scenario
2015	761513,4	66218,6	993758,0	Base Run
2016	761513,4	66218,6	993758,0	Base Run
2017	1370691,08	248154,7	1291558,5	High Production
2018	395346,1	34377,9	704086,0	Shock (SC8)
2019	363404,6	31600,4	691625,0	Shock (SC 8)
2020	754799,3	65634,7	1111506,0	Base Run

Table 6: Production timeline for the mixed bumper harvest and shock scenario 23

After two years of base run production, Zambia experiences another bumper harvest, with production computed as the average of the last five good harvest in 2010-2014. Then, Zambia is hit by an extreme drought lasting two years, before returning to a year with normal base run production. For simplicity, I will call this scenario 23.

The policy that I want to test is for FRA to accumulate large buffer stocks in years with bumper harvests and lock up the excess production (the amount of yearly production that exceeds yearly demand) in their storages with the intention to keep these stocks constant at that level, unless they need to release it in case of emergency. An emergency is defined as a time when the ADESM would fall below a value of 0,8 without policy intervention.

In the case of scenario 23, this policy will cause FRA to keep 515.000 tons of their purchases in the bumper harvest year of 2017 as a strategic reserve, and then release 390.000 tons in the first shock year of 2018 to keep the ADESM over 0,8. This leaves them with 125.000 tons to spend in the second year. The uneven distribution over the two drought years is due to the assumption that they cannot foresee the second drought coming and need to keep the ADESM from collapsing to less than 0,8 in the first year. This assumption seems credible, as it would hardly be justifiable for FRA to not release these emergency relief stocks in the first drought year, just by pointing at the vague possibility of second shock coming up next year.

Running the simulation with and without the policy intervention, we get the following results for our resilience indicator:

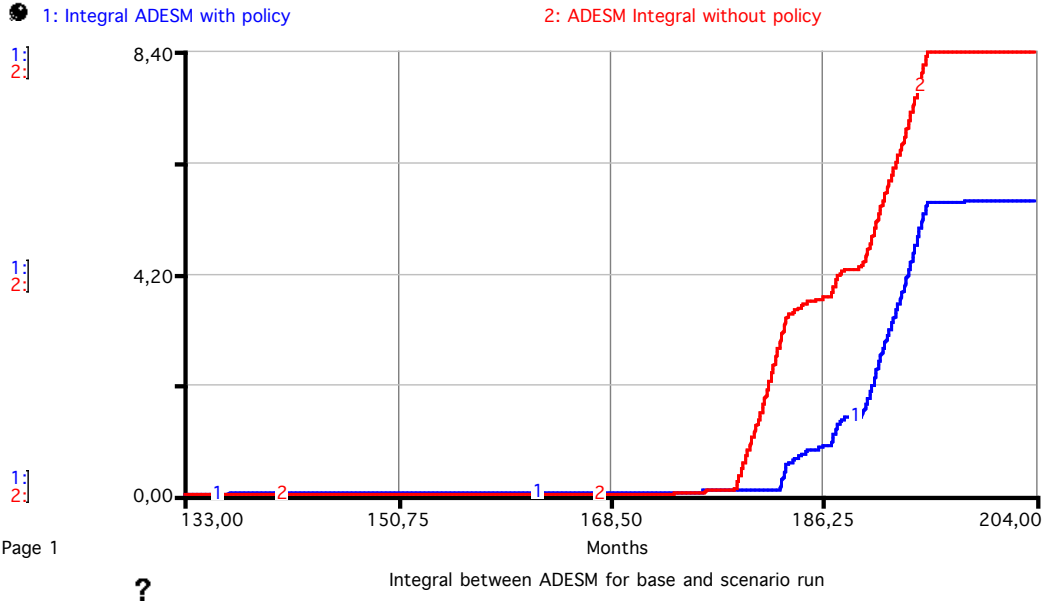


Figure 40: Comparison of ADESM integral between base and scenario 23 run for a “no policy” and a “policy run”

Looking at figure 40, we can see that the ADESM performs significantly better when the policy is in place. The “no policy” run of the scenario featured a final integral between the scenario ADESM and the base run ADESM of 8,39 – while the integral in the “with policy” run only amounted 5,56. This is a reduction by more than one third. Note that the total

production over the years is exactly the same in both runs; the only change is the policy of FRA to store bigger amounts of maize in surplus years and not export the excess maize at the end of the respective surplus year. We can thus conclude that an intelligent storage policy by FRA that exploits the frequent occurrence of surplus harvest years can significantly enhance the resilience of the value chain to production shocks – without any exogenous help or inputs from outside Zambia.

9.3 Feasibility of the Proposed Policy

To conclude the policy analysis part, I want to address the feasibility of the proposed policy. While I have argued that it is neither desirable nor politically feasible to accumulate maize buffer stocks in years of structural maize deficit, the policy proposed and tested in section 9.2 appears to be useful and feasible, as I will show in this section. Possible frictions that might hinder the implementation of the proposed policy can arise from political opposition, storage capacity problems leading to high losses, and funding shortfalls for FRA. I will discuss these problems in turn below.

Looking at **political pressures** that always have a big influence on the decisions taken in politically controlled organizations like FRA, I can see no reason why an accumulation of excess maize in surplus years should trigger political resistance or public outrage.

Loss of maize in FRA storages is actually a very valid concern when trying to implement a policy that requires storing large amounts of maize for long times, potentially over years. While FRA does possess large shed capacities, maize stored in sheds is subject to excessive losses after just a few months of residence time: after one year, we can expect a loss ratio of more than 50% and after 1,5 years even more than 80% (cf. appendix C.3). However, Bou Schreiber (2015) expects FRA to keep on increasing their silo construction so that by the end of 2019, they will have silo capacities of nearly 250.000 tons. This means that a great portion of the maize can be stored in a way that produces almost no significant losses (less

than 3% even after 1,5 years of storage time).¹⁰ Furthermore, if FRA keeps up a steady flow of maize through their storage by mixing and selling maize from last year while stocking up fresh maize, they can limit the residence time and thus the loss ratio to reasonable amounts, even in the sheds. I therefore believe that the storage loss problem can be adequately addressed and will ultimately not hinder the implementation of the proposed policy.

The biggest threat for implementation is in my opinion the fact that FRA would need steady and significant funding over a long time in order to properly execute the storage policy proposed. **Funding for FRA** has been fluctuating quite a lot over the decades and was always subject to often-arbitrary discretionary political decisions (N. Mason, 2011). Furthermore, funding a storage programme will not immediately bring benefits that can be presented to the electorate and there are opportunity costs of allocating funds to the proposed policy, since that money then cannot be used for other, maybe more popular programmes like consumer price subsidies or other poverty reduction measures. I therefore see a real danger that policymakers might, especially in pre-election periods, re-allocate the funds from FRA's buffer stock programme to other measures that reap instant benefits for the population. However, in the end the funding decisions depend on the government's will to follow through with a policy and it therefore *can* work if there is sufficient political will to do it.

9.4 Change in FRA's Sales Policy

Another change in policy I strongly want to suggest is that FRA should start selling maize to grain retailers supplying the informal value chain. The current policy of just selling to big commercial millers actually "locks up" maize in the formal value chain, which is eventually often either exported under unfavourable terms or lost in inappropriate FRA storages, while customers in the informal value chain at the same time cannot satisfy their demand for cheap grain and have to reduce consumption. This obviously inefficient policy leads to

¹⁰ For details on the storage loss ratios, see appendix C.3

the ADESM taking on a value of around 0,84 instead of 1 even in surplus years, as can be seen for the years 2010-12 (months 73 – 96) in figure 41.

This problem can easily be avoided by a simple policy change requiring FRA to open their sales to grain retailers as well. This policy would actually help them fulfil their original mandate – increasing food security for the Zambian population as a whole – much better and more efficient. To illustrate the effects of this policy, I simulated the ADESM for the months 73-96 with and without the proposed FRA sales policy. The results in figure 41 show that the performance of the ADESM would have been enhanced significantly.

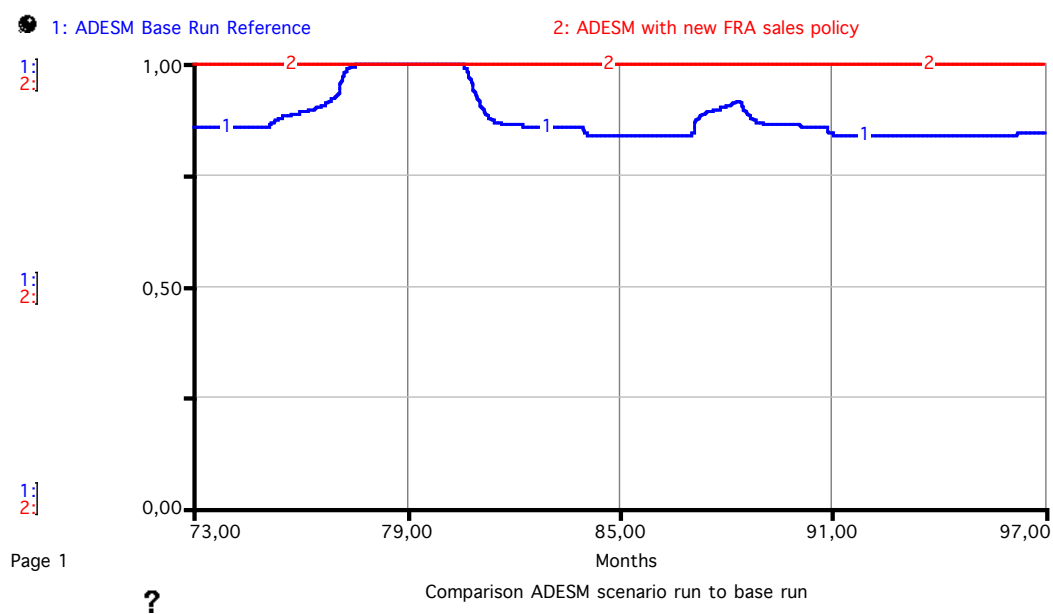


Figure 41: ADESM with and without proposed new FRA sales policy

Concerning feasibility of this policy change, I do not see any big obstacles to implementation. Since FRA has maize storages all over the country, FRA officials could just go there during a number of fixed sales days and administer the exchange of maize against money – much like they do when they buy maize grain from smallholders, just the other way around. Moreover, such a policy change can be expected to be popular in the electorate, as helps the majority of consumers to gain better access to their preferred form of maize.

10. Conclusion

In the first part of this chapter, I will shortly revisit the work done in the thesis and relate it back to the research questions and objectives, as well as answering the central research question and summarize the insights gained. In the second part, I will deliberate the usefulness of the resilience framework used; and in the final part discuss the limitations of my work and give clues to where further work might be necessary and desirable.

10.1 Overview of Results

Chapter 1 introduced the problem and the guiding research questions and objectives for this study, as well as the research design used. Chapter 2 further elaborated on the background of the problem by explaining the concept of food security and how it is connected to the situation of the maize sector in Zambia, thereby placing my research in the context of already existing literature on the topic. Chapter 3 then established the methodological framework by operationalizing the concept of resilience for quantitative measurement in SD models and establishing the central resilience indicator, the ADESM. This part set the stage for being able to answer the research questions and accomplished research objectives 1 and 2.

Chapter 4 then introduced the simulation model, discussed how it was grounded in different sources and connected it to the literature, thereby answering research questions 1 and 2. We learned that the maize value chain in Zambia is not structured like a classical value chain in an industrial country, but has many peculiarities – including the strong influence of FRA, the lack of a developed wholesale sector and the execution of milling processes by the consumers themselves. It further became clear that the value chain is effectively divided in an informal value chain mainly operated by small-scale informal

actors, where customers buy grain and produce the cheaper self-hammer-milled whole grain meal themselves; and a formal value chain involving larger economic agents with a more formalized structure that sell readymade and more expensive roller meal to customers.

Chapter 5 discussed the base run by explicating the rationale behind the external inputs and explaining the model's behaviour. It became clear that the model's key parameters exhibited strong seasonal fluctuations and that informal customers respond to changes in the availability of grain by reducing and substituting maize consumption. Furthermore, we learned that FRA's policies and differences in the availability of maize in the informal vs. formal value chain in the previous marketing season play a central role in determining the distribution and availability of maize between the two value chains in the current marketing year. Chapter 6 generated confidence in the validity of the model by employing a series of validation tests, thereby together with chapter 4 ensuring that research objective 3 was met.

In chapter 7, I then discussed and justified the choice and operationalization of the different production shock scenarios as a necessary prerequisite for the resilience analysis, thus answering research question 3 and accomplishing research objective 4. The conclusion was that production is most affected through changes in the parameters fertilizer input, exposure to water and cultivated land. The most plausible and relevant scenarios for changes in those parameters were shown to be droughts, fertilizer subsidy cuts, exchange rate shocks and floods. These scenarios were then simulated in chapter 8 and the responses analysed in terms of my resilience framework, thereby answering research question 4 and accomplishing research objective 5. Furthermore, I investigated how the structural properties of the value chain affected its resilience towards production shocks. Finally, chapter 9 encompassed the simulation and discussion of policies that could improve the resilience properties, thus fulfilling research objective 6 and answering research question 5.

It should be clear from this overview how the results of every chapter built on each other to finally enable me, using the results of chapters 8 and 9, to answer the central research question: *What are the resilience properties of the maize value chain in Zambia towards production shocks in terms of ensuring sufficient maize supply, and how can the resilience be improved endogenously?*

The general result was that the resilience of the value chain towards one-year shocks is quite good, as the ADESM exhibits a low initial vulnerability due to the existence of buffer stocks in the chain that can be consumed as a substitute for lacking fresh production. However, as soon as the value chain is faced with several consecutive shocks, resilience is low: the adaptive capacity quickly wears off as buffer stocks are soon depleted after 1-2 years, and the food supply breaks down. We furthermore found that there are two main determinants for the effect that a shock has on the ADESM in the value chain: the change in the current year's production, and the availability of carryover stocks that can act as a buffer.

Yet, as discussed in section 3.2, resilience can only be understood as resilience towards a specific shock, and we therefore needed to disaggregate the results into the different types of shocks. In doing so, we learned that the value chain is quite resilient towards exchange rate shocks due to the dynamic response of the production system assumed, as well as towards flood events causing a loss of cultivated area. In the case of shocks affecting the fertilizer subsidies, the value chain is rather vulnerable when these changes become permanent, but can be expected to show a relatively small vulnerability if the changes only last 1-2 years.

However, the value chain is very vulnerable towards a prolonged drought. While a one-year drought still has only limited impact and its effects on the ADESM can be mitigated through the consumption of carryover stocks; already a second consecutive medium to extreme drought year depletes the buffer stocks and leads to increasingly strong impacts on the maize supply. Finally, in the case of two different types of shocks

hitting the value chain simultaneously or consecutively, resilience has proven to be low. The adaptive capacities in the form of buffer stocks are insufficient to alleviate the effects on the ADESM and the food supply quickly falls to threateningly low levels – even though the marginal impact of a given shock on the maize production decreases as shocks accumulate in a combined scenario.

Concerning the relation between the model's structure and the resilience exhibited towards production shocks by the value chain, we found out that the two consumption adjustment loops have an especially strong impact on the resilience properties due to their direct influence on the computation of the ADESM. The reduction of demand in response to the changing availability of grain in the informal value chain, as well as the behaviour of informal consumers to change to other crops and roller meal when supply in the informal value chain dries up, both significantly improve the resilience in response to a given shock. These coping mechanisms reduce demand for a given supply and therefore improve the ratio that determines the ADESM.

Moreover, the non-FRA smallholder sales switch and the information feedback structure of the informal and formal value chain were shown to affect the distribution of maize between the two value chains. And since consumers respond differently to supply changes in the informal value chain due to the two consumption adjustment loops, this distribution in turn affects the ADESM. Furthermore, the FRA reserves switch structure and the feedback structure of the value chain determine which actors build up how much storage stocks throughout the value chain – which in turn influences the extent of buffer stocks available to mitigate the impact of a given shock on the ADESM.

Analysing policies that can improve the resilience properties, we learned that the key to endogenously improve performance was the creation and maintenance of buffer stocks. However, it became clear that building up carryover stocks in an environment of permanent structural maize deficits was neither desirable in terms of its effect on the resilience metrics, nor politically feasible. Yet, I showed that a smart storage policy, using

FRA's infrastructure and exploiting the frequent occurrence of surplus production years, could significantly improve the resilience towards production shocks. Furthermore, the feasibility of such a policy seemed promising under a few conditions, which were that FRA keeps expanding its silo capacity as predicted by Bou Schreiber (2015), keeps a steady flow of maize through its storages and that the storage programme is backed up by sufficient political will. Lastly, I showed that the often inefficient distribution of maize in between the formal and informal value chain, which can lead to supply shortages even in bumper harvest years, could easily be remedied if FRA changed its sales policy in a way that also allowed sales of maize into the informal value chain.

10.2 Discussion of Methodological Framework

Apart from the main goal of yielding insights about the structure, dynamics and resilience properties of the maize value chain in Zambia, my thesis also served as a test for the usefulness of the framework for quantified measurement of resilience in an SD simulation model. I therefore shortly want to evaluate how the framework has performed.

Comparing this framework to the "usual ways" of analysing the behaviour of SD models by graphically comparing the development of a host of variables, I feel that the firm focus on one metric helped to get a much clearer picture of the value chain's capacity to maintain a sufficient food supply in response to the different production shocks. Using the ADESM integral as a metric, we received a fine relative scale that allowed comparing the strengths of the impact between the different scenarios more precisely. Moreover, the distinction between initial vulnerability and adaptive capacity helped to add further clarity to the discussion of the shock responses.

The major drawback of using this method is probably the lack of an absolute scale – the values of the integral only make sense in relation to each other and cannot be compared to some form of general metric. However, despite this limitation I conclude that working with a clear framework has added focus and clarity to my analysis. I understand that the method is not perfect yet, but am confident that it is an interesting reference point for other

scholars who want to study resilience in more depth using System Dynamics; and that inspiration can be drawn from the evidence of this application to further refine the method.

10.3 Limitations and Areas for Further Work

Just as probably the majority of my fellow thesis writers feel, I would have liked to expand my research much more and cover the topic in greater extent and detail, but had to focus on certain aspects in order to give the subject a manageable scope. This in turn led to a number of limitations for my work that I will discuss below. Since a number of minor limitations have already been discussed throughout the text, such as the assumptions or simplifications made in the modelling process in chapter 4, I will not re-iterate those again here but focus on the bigger picture.

The major limitation of my work is probably the rather strong reliance on external inputs when it comes to determining the resilience properties of the value chain towards production shocks. However, I feel that this reflects the nature of research processes, where one starts out with an initial hypothesis (in my case that more of the resilience properties were determined endogenously), and finds evidence that points in another direction. Nonetheless, even though external inputs play a big role in explaining the different resilience properties shown towards the various scenarios, I would argue that it was still worthwhile to use an SD approach to this problem due to the strong influence that the feedback structure had on the value chain's resilience towards a given production shock (cf. chapter 8.5 and 10.1). Moreover, the fine-grained modelling of the value chain also helped to grasp the strong seasonality of behaviour, which is important to understand when designing appropriate and effective policy responses. Finally, the creation of maize stocks throughout the value chain is to a good degree governed by the endogenous information feedback structure of the value chain.

One limitation concerning the resilience measurement framework was that, due to the strong seasonality in my key indicators, the idea of splitting the behaviour of the resilience metrics in “initial vulnerability” vs. “adaptive capacity” did not work exactly as planned

because there was no steady original trajectory that the ADESM could be compared and return to. However, I tried to incorporate the idea as much as possible by looking at how strongly the integral rises at which points in time, defining the initial rise in the first year of a shock as the initial vulnerability and the slope of the integral rise in later years as an expression of the adaptive capacity. As such, the idea did help to structure the analysis. Furthermore, the resilience framework could not account for compensatory responses in the production sector, which lead to increases in production compared to the base run following a shock event, as for example in the case of the flood loss scenarios (cf. figure 29). However, the better performance in a “business as usual” environment following a shock is not really a concern of resilience analysis, and I therefore feel that this was not a problem in terms of my analysis.

Another limitation is obviously that maize alone, as overwhelmingly important as it is for the food supply in Zambia, does not determine the food security situation on its own. Even though agricultural productivity is probably correlated between different crops, as their yields are determined by similar parameters, one can imagine a year with a bad maize harvest and a good harvest for other crops that may act as a substitute. In that case, a low ADESM for maize might not be so much of a problem, as consumers could relatively easily change to other food sources. To reflect the situation in Zambia more holistically, it would therefore be necessary to model the value chains for other crops as well – something I unfortunately did not have the time and resources to do. However, the literature I consulted suggested that the distribution channels for other important crops in Zambia are structured in a similar way to the maize value chain, so that future research could build on the basic model structure that I carved out for maize, and adapt it to represent the value chains for other crops.

A further limitation is that my work had to focus on the availability dimension of food security due to time limitations, and therefore only incorporates parts of the access dimension. This limited representation of the access dimension through just two feedback loops also leads to the “threshold behaviour” of the ADESM that I discussed in section 8.3.4,

meaning that the ADESM usually either stays at 0,84 or quickly collapses to zero, not representing the intermediate stages in detail. However, this representation might not be too far from reality after all, since maize is such a central staple food that demand can be expected to be rather inelastic – which is the reason why I chose to only incorporate those two availability-to-demand feedback loops that were well grounded in the data available to me and assumed inelasticity otherwise. To investigate the access dimension in the model in greater detail, it would be necessary to explicitly model prices and therefore gather detailed information about them. Since there is hardly enough comprehensive information about prices at the different stages of the value chain, as well as their seasonal fluctuations that drive the demand dynamics, further work in that direction would require field research in Zambia.

Furthermore, I had to limit my resilience analysis to production shocks. Inter alia, this was due to the fact that building the model of the maize value chain took longer than anticipated because it was quite difficult to get the appropriate data from Zambia. On the one hand, this means that future research in this area can benefit quite a lot by building on the insights I already laid down in this thesis. On the other hand, this means that some aspects of resilience could not be included in my work. Following what I discussed in chapter 3.3, it would have also been interesting to look at transportation and energy shocks.

To incorporate transportation shocks, however, one would need to include spatial dimensions into the model, as the impact of shocks affecting the transportation capacity of a given physical flow in the model would depend on the distances covered in that link. A way to go about this could be to compute averages for the distances maize typically travels from stage A to stage B in the value chain. This average could then be used to model the degree of impact that the shocks disturbing the transportation capacity of the flow would unfold. The means of transportation that are typically used in that flow would probably also have to be accounted for in such an effect variable. However, I did not find appropriate

information about this in the secondary data or literature, so that researchers looking at this phenomenon would probably need to go to Zambia for first-hand data collection.

Summing up, I can conclude that even though I gained many interesting new insights over the course of my research, there is still plenty of exciting work to be done to create a more thorough picture of the food security situation in Zambia, the dynamics of the maize value chain and the application of resilience research in System Dynamics.

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APPENDIX

Appendix A: Model Documentation

A.1 Demand Sector

Demand

- $Brewery_demand_per_capita_and_month = 0.000455$
UNITS: metric ton/person-month
DOCUMENT: Calculated from USAID & COMPETE (2009: p.20), stating that there is 70.000 m per year demand as of 2009, which is then divided by Zambia's population in 2009 (12.825.000).
- $Daily_dietary_Intake = 2112$
UNITS: kilocalories/person-day
DOCUMENT: Data from FAO (2014)
- $DAR_breweries = Brewery_demand_per_capita_and_month * Total_Population$
UNITS: metric ton/mo
DOCUMENT: Total demand for maize in terms of maize beer production = DAR for breweries in terms of maize
- $Days_per_year = 365$
UNITS: days/year
- $Demand_satisfied_by_subsistence_production = Yearly_subsistence_Consumption * (1 - Subsistence_loss_ratio_processing_and_storage)$
UNITS: metric ton/year
- $Kcal_per_ton_cornflour = 3600 * 1000$
UNITS: kilocalories/metric ton
DOCUMENT: Data from UNHCR, UNICEF, WFP (2002: annex 5)
- $Maize_ratio_in_nutrition = 0.502$
UNITS: Unitless
DOCUMENT: Data from FAO (2015)
- $Monthly_demand_formal_original = Monthly_non_subsistence_demand * (1 - Ratio_informal_demand)$
UNITS: metric ton/mo
DOCUMENT: The amount of demand for commercially produced roller maize meal when demand in the informal value chain is not limited.
- $Monthly_demand_informal_original = Monthly_non_subsistence_demand * Ratio_informal_demand$
UNITS: metric ton/mo
DOCUMENT: The amount of demand for self-milled hammer meal when supply is not a limiting factor
- $Monthly_non_subsistence_demand = Yearly_non_subsistence_demand / Months_per_year$
UNITS: metric ton/mo
- $Months_per_year = 12$
UNITS: month/year

- $\text{Ratio_grain_consumers_in_rural_populaiton} = 0.95$
 UNITS: Unitless
 DOCUMENT: According to Nyanga (2015a), around 95% of rural consumers prefer to buy grain and only a small class of rural wealthy and civil servants (estimated around 5%) can afford to prefer (and get access to, e.g. on frequent city trips) mealie meal.
- $\text{Ratio_grain_consumers_in_urban_population} = 0.331$
 UNITS: Unitless
 DOCUMENT: Data from: see appendix C.5
- $\text{Ratio_informal_demand} = \text{Ratio_Urban_Population} * \text{Ratio_grain_consumers_in_urban_population} + (1 - \text{Ratio_Urban_Population}) * \text{Ratio_grain_consumers_in_rural_populaiton}$
 UNITS: Unitless
 DOCUMENT: The percentage of demand that goes to grain instead of commercial roller meal when supply is not constrained.
- $\text{Ratio_Urban_Population} = \text{Urban_Population} / (\text{Rural_Population} + \text{Urban_Population})$
 UNITS: Unitless
 DOCUMENT: Urban population as a ratio of total population
- $\text{Subsistence_loss_ratio_processing_and_storage} = 0.12$
 UNITS: Unitless
 DOCUMENT: Yearly loss according to APHLIS calculator (Hodges & Bernard, 2014) with the specifications of 6 month average storage time and Cwa climate: 2,42% Farm transport loss 4,5% Farm storage loss 5% Hammer milling loss = 12% Total yearly loss
- $\text{Total_Population} = \text{Urban_Population} + \text{Rural_Population}$
 UNITS: people (person)
- $\text{Total_daily_maize_demand} = \text{Daily_dietary_Intake} * \text{Total_Population} * \text{Maize_ratio_in_nutrition} / \text{Kcal_per_ton_cornflour}$
 UNITS: metric ton/day
- $\text{Total_yearly_maize_demand} = \text{Total_daily_maize_demand} * \text{Days_per_year}$
 UNITS: metric ton/year
- $\text{Yearly_non_subsistence_demand} = \text{MAX}(0, \text{Total_yearly_maize_demand} - \text{Demand_satisfied_by_subsistence_production})$
 UNITS: metric ton/year
 DOCUMENT: Demand for marketed maize = total demand - demand satisfied by subsistence consumption
- ⊗ $\text{Rural_Population} = \text{GRAPH}(\text{TIME})$
 (7.00, 7.1e+06), (19.0, 7.3e+06), (31.0, 7.4e+06), (43.0, 7.6e+06), (55.0, 7.7e+06), (67.0, 7.9e+06), (79.0, 8.1e+06), (91.0, 8.3e+06), (103, 8.5e+06), (115, 8.7e+06), (127, 8.9e+06), (139, 9.2e+06), (151, 9.4e+06), (163, 9.6e+06), (175, 9.9e+06), (187, 1e+07), (199, 1e+07), (204, 1e+07)
 UNITS: people (person)
 DOCUMENT: Population timeline data from UNDESA (2012)
- ⊗ $\text{Urban_Population} = \text{GRAPH}(\text{TIME})$
 (7.00, 4e+06), (19.0, 4.2e+06), (31.0, 4.4e+06), (43.0, 4.5e+06), (55.0, 4.7e+06), (67.0, 4.9e+06), (79.0, 5.1e+06), (91.0, 5.3e+06), (103, 5.6e+06), (115, 5.8e+06), (127, 6.1e+06), (139, 6.4e+06), (151, 6.6e+06), (163, 6.9e+06), (175, 7.2e+06), (187, 7.6e+06), (199, 7.9e+06), (204, 7.9e+06)
 UNITS: people (person)
 DOCUMENT: Population timeline data from UNDESA (2012)
- ⊗ $\text{Yearly_subsistence_Consumption} = \text{GRAPH}(\text{TIME})$
 (7.00, 821142), (19.0, 621771), (31.0, 775131), (43.0, 621196), (55.0, 603955), (67.0, 1e+06), (79.0, 1.4e+06), (91.0, 1.1e+06), (103, 1.3e+06), (115, 1.1e+06), (127, 1.5e+06), (139, 993758), (151, 1e+06), (163, 1e+06), (175, 1.1e+06), (187, 1.1e+06), (199, 1.1e+06), (204, 1.1e+06)
 UNITS: metric ton/year
 DOCUMENT: Total yearly amount of maize that is produced and consumed by smallholder maize farmers in Zambia for subsistence purposes, and thus never enters the market. Same values as "subsistence production". Data sources: see appendix C.1

A.2 Formal Value Chain

Formal Value Chain

$$\square \text{ Accumulated_age_weight_FRA_maize_slabs}(t) = \text{Accumulated_age_weight_FRA_maize_slabs}(t - dt) + (\text{Increase_age_weight_FRA_slab_maize} - \text{Decrease_age_weight_FRA_slab_maize}) * dt$$

INIT Accumulated_age_weight_FRA_maize_slabs = 1

UNITS: metric ton-Age

DOCUMENT: The "age-tagged" maize is accumulated in this stock. (see chapter 4.6.2)

INFLOWS:

$$\rightarrow \text{Increase_age_weight_FRA_slab_maize} = \text{Current_time} * \text{FRA_purchases}$$

UNITS: age-metric ton/mo

DOCUMENT: When new maize is purchased, the current time is multiplied by the purchase volume (in weight), conceptually accumulating the purchase volume with an "age tag" on it. (see chapter 4.6.2)

OUTFLOWS:

$$\rightarrow \text{Decrease_age_weight_FRA_slab_maize} = \text{Avg_entry_time_slab_maize_FRA} * (\text{Moving_maize_to_sheds} + \text{Loss_slabs_FRA})$$

UNITS: age-metric ton/mo

DOCUMENT: As maize is sold or moved out, old and new are assumed to be mixed for sale, so that on average, the maize sold (or moved to better storage facilities, in case of the first FRA stock) has the average age of all the maize in store. This procedure, as opposed to e.g. selling only the oldest maize first, is followed because the longer maize is on storage, the more its quality is adversely affected by moisture, fungi etc. and the more maize is affected, the lower the price for which it can be sold. Therefore, old maize is mixed with newer maize in order to be able to sell it for a good price. (see chapter 4.6.2) To account for all outflows, also losses must be accounted for.

$$\square \text{ Accumulated_age_weight_FRA_prm_strg}(t) = \text{Accumulated_age_weight_FRA_prm_strg}(t - dt) + (\text{Increase_age_weight_FRA_prm_strg} - \text{Decrease_age_weight_FRA_prm_strg}) * dt$$

INIT Accumulated_age_weight_FRA_prm_strg = 1

UNITS: metric ton-Age

DOCUMENT: The "age-tagged" maize is accumulated in this stock. (see chapter 4.6.2)

INFLOWS:

$$\rightarrow \text{Increase_age_weight_FRA_prm_strg} = \text{Current_time} * (\text{Moving_maize_to_sheds} + \text{FRA_Imports})$$

UNITS: age-metric ton/mo

DOCUMENT: When new maize is purchased, the current time is multiplied by the purchase volume (in weight), conceptually accumulating the purchase volume with an "age tag" on it. (see chapter 4.6.2)

OUTFLOWS:

$$\rightarrow \text{Decrease_age_weight_FRA_prm_strg} = \text{Avg_entry_time_FRA_perm_strg} * (\text{Loss_permanent_FRA_storage} + \text{FRA_Exports} + \text{FRA_Sales})$$

UNITS: age-metric ton/mo

DOCUMENT: As maize is sold or moved out, old and new are assumed to be mixed for sale, so that on average, the maize sold (or moved to better storage facilities, in case of the first FRA stock) has the average age of all the maize in store. This procedure, as opposed to e.g. selling only the oldest maize first, is followed because the longer maize is on storage, the more its quality is adversely affected by moisture, fungi etc. and the more maize is affected, the lower the price for which it can be sold. Therefore, old maize is mixed with newer maize in order to be able to sell it for a good price. (see chapter 4.6.2) To account for all outflows, also losses must be accounted for.

▣▣▣ Comm_Farm_Storage(t) = Comm_Farm_Storage(t - dt) + (Commercial__harvest - Readyng_for_sale - Loss_comm_farm_storage) * dt

INIT Comm_Farm_Storage = 0

TRANSIT TIME = 6

CAPACITY = INF

INFLOW LIMIT = INF

UNITS: metric ton

DOCUMENT: According to Keyser (2007: p.65), large-scale commercial farmers store their maize on average for 6 months so that they can get better prices when they sell at the height of the lean season.

INFLOWS:

↔ Commercial__harvest = IF Yearly__counter >=5 AND Yearly__counter<7 THEN Yearly_commercial__Production/ Main_harvest_months_per_year ELSE 0

UNITS: month

DOCUMENT: Assuming that large-scale commercial millers do not engage in early green harvests, as they want to sell later in the year anyway.

OUTFLOWS:

↔ Readyng_for_sale = CONVEYOR OUTFLOW

UNITS: metric ton/mo

DOCUMENT: This flow signifies that the farmers now (6 months after the harvest) want to market their maize. Due to the structure of using a conveyor stock, I needed to construct an extra outflow and "ready for sales stock" to make the purchase and export flows work.

↔ Loss_comm_farm_storage = LEAKAGE OUTFLOW

LEAKAGE FRACTION = 0.021

LEAK ZONE = 0% to 100%

UNITS: metric ton/mo

DOCUMENT: 2.1% farm storage losses for big farmers according to the APHLIS post-harvest losses calculator with 6 month storage time and Cwa climate (African Postharvest Losses Information System, 2015).

□ Comm_production_for_sale(t) = Comm_production_for_sale(t - dt) + (Readyng_for_sale - Comm_farmers_exports - Commercial_farmers_sales) * dt

INIT Comm_production_for_sale = 0

UNITS: metric ton

DOCUMENT: This flow signifies that the farmers now (6 months after the harvest) want to market their maize. Due to the structure of using a conveyor stock, I needed to construct an extra outflow and "ready for sales stock" to make the purchase and export flows work. The initial value is zero because I feel it is safe to assume that in the years of insufficient production, they sell all their (small) production quickly in November and December: at least over the simulation of the first low-production years, they always sold everything by that time

INFLOWS:

↔ Readyng_for_sale = CONVEYOR OUTFLOW

UNITS: metric ton/mo

DOCUMENT: This flow signifies that the farmers now (6 months after the harvest) want to market their maize. Due to the structure of using a conveyor stock, I needed to construct an extra outflow and "ready for sales stock" to make the purchase and export flows work.

OUTFLOWS:

$$\Leftrightarrow \text{Comm_farmers_exports} = \text{Comm_production_for_sale} / \text{AT_comm_farmers_exports} * \text{Switch_comm_farmers_exports}$$

Switch_comm_farmers_exports

UNITS: metric ton/mo

DOCUMENT: In case they get permission, commercial farmers want to sell everthing abroad (see chapter 4.6.4).

$$\Leftrightarrow \text{Commercial_farmers_sales} = (\text{Gap_miller_grain_strg} / \text{AT_commercial_farmer_sales} + \text{Total_outflows_millers}) * (1 - \text{Switch_comm_farmers_exports})$$

UNITS: metric ton/mo

DOCUMENT: When exports are banned, large-scale commercial farmers sell their grain to big commercial millers on the domestic market. Due to the competetive prices and the ability to sell large quantities in bulk, I assume that millers source preferrably from commercial farmers. (Keyser, 2007: p.65)

$$\square \text{Formal_customer_meal_storage}(t) = \text{Formal_customer_meal_storage}(t - dt) + (\text{Commercial_milling_and_retailing} - \text{Consumption_Formal}) * dt$$

INIT Formal_customer_meal_storage = Des_formal_customer_meal_strg

UNITS: metric ton

DOCUMENT: Initialized in equilibrium.

INFLOWS:

$$\Leftrightarrow \text{Commercial_milling_and_retailing} = \text{OR_milling_and_retailing} * (1 - \text{Waste_Ratio_Roller_Milling})$$

UNITS: metric ton/mo

DOCUMENT: The amount of maize meal output for human consumption equals the total amount of maize that was put into the production (the OR) minus the waste ratio.

OUTFLOWS:

$$\Leftrightarrow \text{Consumption_Formal} = \text{Total_monthly_demand_formal}$$

UNITS: metric ton/mo

$$\square \text{FRA_maize_in_slabs}(t) = \text{FRA_maize_in_slabs}(t - dt) + (\text{FRA_purchases} - \text{Moving_maize_to_sheds} - \text{Loss_slabs_FRA}) * dt$$

INIT FRA_maize_in_slabs = 0

UNITS: metric ton

DOCUMENT: Slabs all around the country are the place where farmers usually first sell thei maize to FRA. Initial value of zero because we start the simulation after the end of FRA's purchasing period in a year where their purchase volume is lower than their built capacity, so that by that time, all maize from the slabs must have been moved to their sheds or silos.

INFLOWS:

$$\Leftrightarrow \text{FRA_purchases} = \text{FRA_domestic_yearly_purchase} / \text{Purchase_periods_per_year} * \text{FRA_purchase_distribution}$$

UNITS: metric ton/mo

INFLOWS:

$$\Leftrightarrow \text{FRA_purchases} = \text{FRA_domestic_yearly_purchase} / \text{Purchase_periods_per_year} * \text{FRA_purchase_distribution}$$

UNITS: metric ton/mo

OUTFLOWS:

$$\Leftrightarrow \text{Moving_maize_to_sheds} = (\text{Total_built_capacity_FRA} - \text{FRA_maize_in_permanent_storage}) /$$

AT_moving_maize_to_permanent_strg

UNITS: metric ton/mo

DOCUMENT: As slabs have signifcantly higher storage losses than sheds or silos, FRA wants to quickly move the maize from the slabs to permanent storage.

$$\Leftrightarrow \text{Loss_slabs_FRA} = \text{FRA_maize_in_slabs} * \text{Loss_Ratio_slabs} / \text{Months_per_yr}$$

UNITS: metric ton/mo

□ $FRA_maize_in_permanent_storage(t) = FRA_maize_in_permanent_storage(t - dt) + (Moving_maize_to_sheds + FRA_Imports - FRA_Sales - FRA_Exports - Loss_permanent_FRA_storage) * dt$

INIT $FRA_maize_in_permanent_storage = 0$

UNITS: metric ton

DOCUMENT: FRA purchased 105.000 tons of maize in the summer of 2003 according to N. M. Mason & Myers (2011). I assume they sold most of it and thus have a reserve of 40.000 tons left in January.

INFLOWS:

↻ $Moving_maize_to_sheds = (Total_built_capacity_FRA - FRA_maize_in_permanent_storage) / AT_moving_maize_to_permanent_strg$

UNITS: metric ton/mo

DOCUMENT: As slabs have significantly higher storage losses than sheds or silos, FRA wants to quickly move the maize from the slabs to permanent storage.

↻ $FRA_Imports = IF\ Yearly_counter \geq 6\ AND\ Yearly_counter < 8\ THEN\ Yearly_Imports / Import_months_per_year\ ELSE\ 0$

UNITS: metric ton/mo

DOCUMENT: I assume that FRA starts their imports, in case they see the need for it due to a lack of domestic production, when it is clear how big the domestic harvest is, which is normally around June when the last parts of the harvest come in.

OUTFLOWS:

↻ $FRA_Sales = MIN(Gap_FRA_reserves / AT_FRA_Sales, (Gap_miller_grain_strg / AT_FRA_Sales + Total_outflows_millers) - Commercial_farmers_sales - Commercial_maize_assemblage)$

UNITS: metric ton/mo

DOCUMENT: Buying from FRA is the millers' least preferred sourcing option, as it usually takes longer to get the maize due to bureaucracy, and because FRA sells at a more expensive price to get the money back they spent when they purchased the maize at above-market prices from the smallholders. The MIN function ensures that only the excess maize is sold and FRA keeps its desired reserves.

↻ $FRA_Exports = IF\ Yearly_counter \geq 3\ AND\ Yearly_counter < 6\ THEN\ MAX(Zero_mt_per_month, Gap_FRA_reserves / AT_FRA_exports - FRA_Sales)\ ELSE\ 0$

UNITS: metric ton/mo

DOCUMENT: As the indications come in for the crop Forecast Survey come in every February/March and FRA has updated its desired reserves, excess maize stocks are sold until the FRA's new purchasing season starts. However, for two reasons this only happens in the case that there is no sufficient domestic demand: 1. FRA's main goal is to service domestic food supply. 2. Selling abroad might be the better option than letting maize rot away in sheds, but exports are often sold at a loss because FRA paid above-market prices for the maize purchase.

↻ $Loss_permanent_FRA_storage = FRA_maize_in_permanent_storage * Loss_ratio_prm_FRA_strg / Months_per_yr$

UNITS: metric ton/mo

□ $Millers_grain_storage(t) = Millers_grain_storage(t - dt) + (Commercial_maize_assemblage + Commercial_farmers_sales + FRA_Sales - Roller_milling_waste - Sold_to_breweries - Commercial_milling_and_retailing) * dt$
INIT $Millers_grain_storage = 0$

UNITS: metric ton

DOCUMENT: Initial value of zero because we start late in the lean season in a deficit production year, so that millers can be assumed to run low on reserves at that point.

INFLOWS:

↻ $Commercial_maize_assemblage = (Gap_miller_grain_strg/AT_commercial_maize_assemblage + Total_outflows_millers - Commercial_farmers_sales) * Switch_non_FRA_smallholder_sales$

UNITS: metric ton/mo

DOCUMENT: Grain assemblers from smallholders are the second-best option in terms of miller preferences for sourcing maize, wherefore the commercial farmer sales flow is deducted from the demand. They also sell at competitive prices, but have a more scattered structure. The flow is furthermore influenced by the "non-FRA smallholder sales switch".

↻ $Commercial_farmers_sales = (Gap_miller_grain_strg/AT_commercial_farmer_sales + Total_outflows_millers) * (1 - Switch_comm_farmers_exports)$

UNITS: metric ton/mo

DOCUMENT: When exports are banned, large-scale commercial farmers sell their grain to big commercial millers on the domestic market. Due to the competitive prices and the ability to sell large quantities in bulk, I assume that millers source preferably from commercial farmers. (Keyser, 2007: p.65)

↻ $FRA_Sales = MIN(Gap_FRA_reserves/AT_FRA_Sales, [(Gap_miller_grain_strg/AT_FRA_Sales + Total_outflows_millers) - Commercial_farmers_sales - Commercial_maize_assemblage])$

UNITS: metric ton/mo

DOCUMENT: Buying from FRA is the millers' least preferred sourcing option, as it usually takes longer to get the maize due to bureaucracy, and because FRA sells at a more expensive price to get the money back they spent when they purchased the maize at above-market prices from the smallholders. The MIN function ensures that only the excess maize is sold and FRA keeps its desired reserves.

OUTFLOWS:

↻ $Roller_milling_waste = (Commercial_Milling_and_retailing + Sold_to_breweries) * Waste_Ratio_Roller_Milling$

UNITS: metric ton/mo

DOCUMENT: Outflow of total losses arising in the roller milling process.

↻ $Sold_to_breweries = OR_breweries * (1 - Waste_Ratio_Roller_Milling)$

UNITS: metric ton/mo

DOCUMENT: The amount of maize meal that is actually sold to breweries equals the amount that was put into the production (order rate breweries) minus the loss ratio.

↻ $Commercial_milling_and_retailing = OR_milling_and_retailing * (1 - Waste_Ratio_Roller_Milling)$

UNITS: metric ton/mo

DOCUMENT: The amount of maize meal output for human consumption equals the total amount of maize that was put into the production (the OR) minus the waste ratio.

- $Smallholder_farm_grain_storage(t) = Smallholder_farm_grain_storage(t - dt) + (Smallholder_surplus_main_harvest + Smallholder_surplus_green_harvest - FRA_purchases - Informal_grain_retailing - Commercial_maize_assemblage - SH_farm_storage_loss) * dt$
 INIT $Smallholder_farm_grain_storage = 0$
 UNITS: metric ton
 DOCUMENT: Initial value of zero because we start late in the lean season in a deficit production year, so that it is very likely that smallholders have sold all their surplus production by that point.
 INFLOWS:
 - ↻ $Smallholder_surplus_main_harvest = IF\ Yearly_counter \geq 5\ AND\ Yearly_counter < 7\ THEN\ Yearly_SH_surplus_production * Ratio_main_harvest / Main_harvest_months_per_year\ ELSE\ 0$
 UNITS: metric ton/mo
 - ↻ $Smallholder_surplus_green_harvest = IF\ Yearly_counter \geq 3\ AND\ Yearly_counter < 5\ THEN\ Yearly_SH_surplus_production * (1 - Ratio_main_harvest) / Green_harvest_months_per_year\ ELSE\ 0$
 UNITS: metric ton/mo
 OUTFLOWS:
 - ↻ $FRA_purchases = FRA_domestic_yearly_purchase / Purchase_periods_per_year * FRA_purchase_distribution$
 UNITS: metric ton/mo
 - ↻ $Informal_grain_retailing = MAX(Zero_mt_per_month, DAR_informal_retailing) * Switch_non_FRA_smallholder_sales$
 UNITS: metric ton/mo
 DOCUMENT: The grain retailing is determined by the DAR of the consumers and the switch prohibiting or allowing non-FRA smallholder sales.
 - ↻ $Commercial_maize_assemblage = (Gap_miller_grain_strg / AT_commercial_maize_assemblage + Total_outflows_millers - Commercial_farmers_sales) * Switch_non_FRA_smallholder_sales$
 UNITS: metric ton/mo
 DOCUMENT: Grain assemblers from smallholders are the second-best option in terms of miller preferences for sourcing maize, wherefore the commercial farmer sales flow is deducted from the demand. They also sell at competitive prices, but have a more scattered structure. The flow furthermore influenced by the "non-FRA smallholder sales switch".
 - ↻ $SH_farm_storage_loss = Smallholder_farm_grain_storage * Farm_strg_loss_ratio_per_month$
 UNITS: metric ton/mo
 DOCUMENT: Monthly storage losses in smallholder farmer grain storages.
- $AT_comm_farmers_exports = 0.5$
 UNITS: month
 DOCUMENT: Two weeks according to Nyanga (2015a) in case the export permission is (already) granted - which is the prerequisite for the commercial farmers export switch to turn to 1.00 AT = adjustmet time
- $AT_commercial_farmer_sales = 0.25$
 UNITS: month
 DOCUMENT: Adjustmet times for miller purchases: commercial and smallholder farmers service demand within 1 week; while FRA takes longer due to bureaucracy, around 2 weeks. (Nyanga, 2015a)
- $AT_commercial_maize_assemblage = 0.25$
 UNITS: month
 DOCUMENT: Adjustmet times for miller purchases: commercial and smallholder farmers service demand within 1 week; while FRA takes longer due to bureaucracy, around 2 weeks. (Nyanga, 2015a)
- $AT_FRA_exports = 1$
 UNITS: months (mo)
 DOCUMENT: Nyanga (2015a) assumes 1 month AT adjustment time for FRA exports, as FRA is usually slower than the private sector due to bureaucratic hurdles in the system.

- $AT_FRA_Sales = 0.5$
 UNITS: month
 DOCUMENT: Adjustmet times for miller purchases: commercial and smallholder farmers service demand within 1 week; while FRA takes longer due to bureaucracy, around 2 weeks. (Nyanga, 2015a)
- $AT_milling_and_retailing = 0.6$
 UNITS: months (mo)
 DOCUMENT: Retailers refill their stock every 1-2 weeks. On top of that, there is the milling and transportation process, that can take up to 1 week in case of inter-regional transport. Since most commercial millers are concentrated in Lusaka, we can assume most transports are inter-regional. In total, 2-3 weeks seems therefore like suitable adjustment time. (Nyanga, 2015b)
- $AT_moving_maize_to_permanent_strg = 0.1$
 UNITS: months (mo)
 DOCUMENT: Moving maize from the slabs to the permanent storage (sheds or silos) should not take more than 3 days, as FRA has contractors doing that for them so that we assume the following distribution: 1 day for getting the maize from the slab, 1 days for transporting it and 1 day for offloading it to the permanent depot. (Nyanga, 2015a)
- $Avg_entry_time_FRA_perm_strg = IF\ FRA_maize_in_permanent_storage < 0.01\ THEN\ Current_time\ ELSE\ Accumulated_age_weight_FRA_prm_strg / FRA_maize_in_permanent_storage$
 UNITS: Age
 DOCUMENT: The average time when the accumulated maize entered the storage can be deduced by simply dividing the "age-tagged-maize" stock by the current storage, so that only the average age comes out of the calculation. The IF function prevents the average to go to extreme values in the case of seasonal fluctuations that bring the maize storage to zero.
- $Avg_entry_time_slab_maize_FRA = IF\ FRA_maize_in_slabs < 0.01\ THEN\ Current_time\ ELSE\ Accumulated_age_weight_FRA_maize_slabs / FRA_maize_in_slabs$
 UNITS: Age
 DOCUMENT: The average time when the accumulated maize entered the storage can be deduced by simply dividing the "age-tagged-maize" stock by the current storage, so that only the average age comes out of the calculation. The IF function prevents the average to go to extreme values in the case of seasonal fluctuations that bring the maize storage to zero.
- $CT_grain_miller_storage = 1$
 UNITS: month
 DOCUMENT: I assume that millers want to cover one month's demand with their maize storage. That would strike a balance between guarding against the observed fluctuations in the market and keeping storage costs at a reasonable level.
- $DAR_milling_and_retailing = MAX(0, Consumption_Formal + Gap_formal_customer_meal_strg / AT_milling_and_retailing)$
 UNITS: metric ton/mo
 DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, the Desired Acquisition Rate is calculated by accounting for the closing of the gap between the desired and actual storage, and then adding the compensation for the outflows.
- $Desired_FRA_reserves_adjusted = Desired_FRA_reserves_original * Switch_FRA_reserves$
 UNITS: metric ton
 DOCUMENT: The desired FRA reserves after they have been changed according to the current maize supply situation in the country: if there is dire need for maize, FRA will not keep it locked up in their storage.
- $Desired_miller_grain_strg = (OR_milling_and_retailing + OR_breweries) * CT_grain_miller_storage$
 UNITS: metric ton
 DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, desired storage is determined by the coverage time and the monthly demand.

- $Des_formal_customer_meal_strg = Total_monthly_demand_formal * CT_inf_customer_meal_strg$
 UNITS: metric ton
 DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, desired storage is determined by the coverage time and the monthly demand.
- $Farm_strg_loss_ratio_per_month = 0.00678$
 UNITS: per month (1/mo)
 DOCUMENT: Losses are exponential in reality, but this is an approximation from the APHLIS post-harvest losses calculator's data for losses in smallholder farmer storage with residence times between 4-6 months and Cwa climate (African Postharvest Losses Information System, 2015). Exponential loss calculations need to involve the RT, which cannot be computed with all the strong seasonal fluctuations.
- $Gap_formal_customer_meal_strg = Des_formal_customer_meal_strg - Formal_customer_meal_storage$
 UNITS: metric ton
- $Gap_FRA_reserves = MAX(0, FRA_maize_in_permanent_storage - Desired_FRA_reserves_adjusted)$
 UNITS: metric ton/mo
 DOCUMENT: The amount of maize that FRA has on storage which exceeds its desired reserves, that amount is free for sale.
- $Gap_miller_grain_strg = Desired_miller_grain_strg - Millers_grain_storage$
 UNITS: metric ton
- $Green_harvest_months_per_year = 2$
 UNITS: month/year
 DOCUMENT: Green harvest comes in March and April (Nyanga, 2015b), for simplicity I assume even distribution over the two months.
- $Import_months_per_year = 2$
 UNITS: months (mo)
 DOCUMENT: I assume that FRA imports over the course of two months, as the bureaucratic processes with the government and FRA (incl. lifting or changing import bans or restrictions) always takes a fairly long time.
- $Loss_ratio_prm_FRA_strg = Loss_Ratio_sheds * Ratio_maize_in_sheds_FRA + Loss_ratio_silos * (1 - Ratio_maize_in_sheds_FRA)$
 UNITS: Unitless
 DOCUMENT: The combined loss ratio for maize in permanent storage equals the sum of the loss ratio for silos times the ratio of maize that is stored in silos, and the loss ratio for sheds times the ratio of maize that is stored in sheds.
- $Main_harvest_months_per_year = 2$
 UNITS: month/year
 DOCUMENT: Main harvest comes in May and June (Nyanga, 2015b), for simplicity I assume even distribution over the two months.
- $Months_per_yr = 12$
 UNITS: months (mo)
 DOCUMENT: Since losses are calculated in years in Bou Schreiber's (2015) framework, the time horizon needs to be transformed to years with this variable.
- $OR_breweries = DAR_breweries / (1 - Waste_Ratio_Roller_Milling)$
 UNITS: metric ton/mo
 DOCUMENT: Since the millers can be assumed to know their production process well, they account here for the loss, so that maize meal demand by breweries is topped up by the amount of loss that will occur in the roller milling process. This yields the internal order rate, which determine the amount of maize that I put into the production.

- $OR_milling_and_retailing = DAR_milling_and_retailing / (1 - Waste_Ratio_Roller_Milling)$
 UNITS: metric ton/mo
 DOCUMENT: Since the millers can be assumed to know their production process well, they account here for the loss, so that demand by retailers is topped up by the amount of loss that will occur in the roller milling process. This yields the internal order rate, which determine the amount of maize that i put into the production.
- $Purchase_periods_per_year = 1$
 UNITS: per year (1/yr)
 DOCUMENT: Variable necessary to transform the yearl to monthly data.
- $Ratio_main_harvest = 0.925$
 UNITS: Unitless
 DOCUMENT: Nyanga (2015b) estimated that 90-95% of the harvest are in the main harvest and corollary only 10-5% in the green harvest.∑ therefore took the mean of the estimates and assigned 92.5% to the main harvest.
- $Relative_age_FRA_perm_strg = Current_time - Avg_entry_time_FRA_perm_strg$
 UNITS: Age
 DOCUMENT: To measure the actual time that the maize has spent in this storage (the ,Áúrelative age,Äù), one simply has to take the difference between the current time and the average age
- $Relative_age_maize_slabs = Current_time - Avg_entry_time_slab_maize_FRA$
 UNITS: Age
 DOCUMENT: To measure the actual time that the maize has spent in this storage (the ,Áúrelative age,Äù), one simply has to take the difference between the current time and the average age
- $Total_monthly_demand_formal = Monthly_demand_formal_original + Inf_demand_to_formal_spillover_adjusted$
 UNITS: metric ton/mo
 DOCUMENT: The amount of demand for commercially produced roller maize meal when the spill-over from consumers from the informal value chain is accounted for.
- $Total_outflows_millers = Commercial_milling_and_retailing + Sold_to_breweries + Roller_milling_waste$
 UNITS: metric ton/mo
- $Waste_Ratio_Roller_Milling = 0.11$
 UNITS: Unitless
 DOCUMENT: According to Keyser (2007: table 49), roller milling produces 2% waste and 9% bran meal. Since bran meal is not mixed into the commercially sold roller meal, it is considered "waste" here.
- $Yearly_counter = COUNTER(1,13)$
 UNITS: month
 DOCUMENT: Counts the months of the year from 1,0 to 12,99 - with 1 being January, 2 being February and so forth.
- $Zero_mt_per_month = 0$
 UNITS: metric ton/mo
 DOCUMENT: Dummy variable for zero, as iThink sometimes cannot compute the $MAX(0,x)$ functions in the unit check with just a number for zero.
- ⊗ $Current_time = GRAPH(TIME)$
 (1.00, 0.00), (204, 204)
 UNITS: Age
 DOCUMENT: This variables simply counts the current month we are in at that moment in the simulation to be able to "age-tag" the maize as it comes in.

-  Desired_FRA_reserves_original = GRAPH(TIME)
 (3.00, 0.00), (15.0, 0.00), (27.0, 0.00), (39.0, 0.00), (51.0, 0.00), (63.0, 0.00), (75.0, 131786), (87.0, 236984), (99.0, 156750), (111, 63359), (123, 154696), (135, 91379), (147, 91379), (159, 91379), (171, 91379), (183, 91379), (195, 91379), (204, 91379)
 UNITS: metric ton
 DOCUMENT: Assuming that FRA updates it's desired reserves for the new marketing season as the results of the Crop Forecast Survey come in every February/March. (Nyanga, 2015a) Data sources: see appendix C.2
-  FRA_domestic_yearly_purchase = GRAPH(TIME)
 (1.00, 105279), (13.0, 78667), (25.0, 389510), (37.0, 396450), (49.0, 73876), (61.0, 198630), (73.0, 878570), (85.0, 1.6e+06), (97.0, 1e+06), (109, 422391), (121, 1e+06), (133, 380757), (145, 371169), (157, 369485), (169, 372556), (181, 378167), (193, 385056), (204, 385056)
 UNITS: metric ton/year
 DOCUMENT: Amount of maize that FRA purchases in the current season or year. Data sources: see appendix C.2
-  FRA_purchase_distribution = GRAPH(Yearly__counter)
 (1.00, 0.00), (1.50, 0.00), (2.00, 0.00), (2.50, 0.00), (3.00, 0.00), (3.50, 0.00), (4.00, 0.00), (4.50, 0.00), (5.00, 0.00), (5.50, 0.00), (6.00, 0.00), (6.50, 0.0598), (7.00, 0.194), (7.50, 0.452), (8.00, 0.588), (8.50, 0.452), (9.00, 0.194), (9.50, 0.0598), (10.0, 0.00), (10.5, 0.00), (11.0, 0.00), (11.5, 0.00), (12.0, 0.00), (12.5, 0.00), (13.0, 0.00)
 UNITS: per month (1/mo)
 DOCUMENT: For FRA purchases, there is an officially government-announced purchasing season that usually lasts from beginning/middle of June until the end of September or beginning of October, reaching the highest purchase volume around the middle of the purchasing season during late July and early August. I assumes a roughly bell-shaped distribution. (Nyanga, 2015b) I therefore used the values of a normal distribution that amounts to exactly one as ratio values to be multiplied with the purchase goal to include the purchase distribution.
-  Loss_Ratio_sheds = GRAPH(Relative_age_FRA_perm_strg)
 (1.00, 0.00715), (2.00, 0.0161), (3.00, 0.0182), (4.00, 0.0447), (5.00, 0.065), (6.00, 0.101), (7.00, 0.15), (8.00, 0.206), (9.00, 0.269), (10.0, 0.341), (11.0, 0.422), (12.0, 0.512), (13.0, 0.611), (14.0, 0.719), (15.0, 0.836)
 UNITS: Unitless
 DOCUMENT: Data sources: see appendix C.3
-  Loss_ratio_silos = GRAPH(Relative_age_FRA_perm_strg)
 (1.00, 0.00), (2.00, 0.0028), (3.00, 0.0081), (4.00, 0.0082), (5.00, 0.0083), (6.00, 0.0136), (7.00, 0.0166), (8.00, 0.0186), (9.00, 0.0204), (10.0, 0.022), (11.0, 0.0234), (12.0, 0.0246), (13.0, 0.0256), (14.0, 0.0264), (15.0, 0.027), (16.0, 0.0274), (17.0, 0.0276), (18.0, 0.0276)
 UNITS: Unitless
 DOCUMENT: Data sources: see appendix C.3
-  Loss_Ratio_slabs = GRAPH(Relative_age_maize_slabs)
 (1.00, 0.0571), (2.00, 0.0661), (3.00, 0.0683), (4.00, 0.0946), (5.00, 0.115), (6.00, 0.151), (7.00, 0.2), (8.00, 0.256), (9.00, 0.319), (10.0, 0.391), (11.0, 0.472), (12.0, 0.562), (13.0, 0.661), (14.0, 0.769), (15.0, 0.886)
 UNITS: Unitless
 DOCUMENT: Data sources: see appendix C.3
-  Yearly_Imports = GRAPH(TIME)
 (1.00, 9400), (13.0, 38950), (25.0, 119700), (37.0, 1458), (49.0, 1015), (61.0, 42027), (73.0, 5704), (85.0, 2911), (97.0, 0.00), (109, 0.00), (121, 0.00), (133, 0.00), (145, 0.00), (157, 0.00), (169, 0.00), (181, 0.00), (193, 0.00), (204, 0.00)
 UNITS: metric ton/year
 DOCUMENT: Data sources: see appendix C.2

- Yearly_commercial__Production = GRAPH(TIME)
 - (1.00, 48578), (13.0, 65613), (25.0, 84960), (37.0, 97099), (49.0, 85578), (61.0, 229893), (73.0, 331960), (85.0, 233484), (97.0, 220521), (109, 195793), (121, 259016), (133, 66219), (145, 64551), (157, 64258), (169, 64792), (181, 65768), (193, 66966), (204, 66966)
 - UNITS: metric ton/year
 - DOCUMENT: Total yearly maize production of large-scale commercial farmers in Zambia. Data sources: see appendix C.1
- Yearly_SH_surplus_production = GRAPH(TIME)
 - (1.00, 343878), (13.0, 178803), (25.0, 564348), (37.0, 647862), (49.0, 522033), (61.0, 613356), (73.0, 1.1e+06), (85.0, 1.7e+06), (97.0, 1.4e+06), (109, 1.2e+06), (121, 1.6e+06), (133, 761513), (145, 742338), (157, 738971), (169, 745113), (181, 756334), (193, 770112), (204, 770112)
 - UNITS: metric ton/year
 - DOCUMENT: Total yearly maize production that is sold for marketing by smallholder farmers in Zambia. Data sources: see appendix C.1

A.3 Informal Value Chain

- Informal_customer_grain_storage(t) = Informal_customer_grain_storage(t - dt) + (Informal_grain_retailing - Hammer_Milling_Loss - Hammer_Milling_Output) * dt
 - INIT Informal_customer_grain_storage = 0
 - UNITS: metric ton
 - DOCUMENT: Initial value of zero because we start late in the lean season in a deficit production year.
 - INFLOWS:
 - ↻ Informal_grain_retailing (IN SECTOR: Formal Value Chain)
 - OUTFLOWS:
 - ↻ Hammer_Milling_Loss = Hammer_Milling_Output*Loss_Ratio_Hammer_Milling
UNITS: metric ton/mo
 - ↻ Hammer_Milling_Output = MAX(0,OR_Hammer_Milling*(1-Loss_Ratio_Hammer_Milling))
UNITS: metric ton/mo
DOCUMENT: The actually consumable output of the hammer milling process is the order rate (which amount of maize was put into the mill) minus the loss ratio.
- Informal_customer_meal_storage(t) = Informal_customer_meal_storage(t - dt) + (Hammer_Milling_Output - Consumption_Informal) * dt
 - INIT Informal_customer_meal_storage = Desired_Inf_customer_meal_storage
 - UNITS: metric ton
 - DOCUMENT: Initiaized in equilibrium with the desired stock.
 - INFLOWS:
 - ↻ Hammer_Milling_Output = MAX(0,OR_Hammer_Milling*(1-Loss_Ratio_Hammer_Milling))
UNITS: metric ton/mo
DOCUMENT: The actually consumable output of the hammer milling process is the order rate (which amount of maize was put into the mill) minus the loss ratio.
 - OUTFLOWS:
 - ↻ Consumption_Informal = Monthly_Demand_Informal
UNITS: metric ton/mo

- $\text{Perc_ratio_inf_retailing_not_fulfilled}(t) = \text{Perc_ratio_inf_retailing_not_fulfilled}(t - dt) + (\text{Chng_in_perc_ratio_inf_retailing_not_fulfilled}) * dt$
INIT Perc_ratio_inf_retailing_not_fulfilled = 1
UNITS: Unitless
DOCUMENT: Initial value of 1 indicates that the grain supply has fallen to zero, as we are deep into the lean season of a deficit production year at the beginning of the simulation.
INFLOWS:
 - ✦ Chng_in_perc_ratio_inf_retailing_not_fulfilled = $(\text{Ratio_inf_retailing_not_fulfilled} - \text{Perc_ratio_inf_retailing_not_fulfilled}) / \text{AT_perception_ratio_inf_retailing_not_fulfilled}$
UNITS: per month (1/mo)
- $\text{AT_hammer_milling} = 0.034$
UNITS: months (mo)
DOCUMENT: Milling is done in one day, as consumers normally bring their grain to the mill in the morning and in a matter of hours, the maize is milled and they can the meal back in the afternoon (Nyanga, 2015a). Furthermore, hammer mills are all around the country so that no long journeys are required. AT = Adjustment time
- $\text{AT_informal_retailing} = 0.1$
UNITS: months (mo)
DOCUMENT: I assume that it takes roughly only 3 days in total to buy, transport and sell the grain (1 day for each activity), since the grain retailing business is mostly run locally.
- $\text{AT_perception_ratio_inf_retailing_not_fulfilled} = 0.25$
UNITS: months (mo)
DOCUMENT: I assume that consumers do not immediately change their consumption patterns when there is one day where they cannot purchase the desired amount of grain, but wait for a few days (1 week) until they adapt their consumption to the supply scarcity.
- $\text{CT_informal_grain_storage} = 2.5$
UNITS: months (mo)
DOCUMENT: When maize grain is well available, consumers want to store grain covering 2-3 months' consumption according to Nyanga (2015b). I took the average of that estimate as the value for this parameter. CT = Coverage time
- $\text{CT_inf_customer_meal_strg} = 1$
UNITS: month
DOCUMENT: Consumers in the formal and informal value chain alike do not want to store their maize meal for more than 1 month because meal is more susceptible to losses than grain. Source: Nyanga (2015a) CT = Coverage Time
- $\text{DAR_hammer_milling} = \text{MAX}(0, \text{Consumption_Informal} + \text{Gap_informal_meal_storage} / \text{AT_hammer_milling})$
UNITS: metric ton/mo
DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, the Desired Acquisition Rate is calculated by accounting for the closing of the gap between the desired and actual storage, and then adding the compensation for the outflows.
- $\text{DAR_informal_retailing} = \text{MAX}(0.01, \text{Hammer_Milling_Output} + \text{Hammer_Milling_Loss} + \text{Gap_inf_customer_grain_storage} / \text{AT_informal_retailing})$
UNITS: metric ton/mo
DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, the Desired Acquisition Rate is calculated by accounting for the closing of the gap between the desired and actual storage, and then adding the compensation for the outflows. The MAX function with 0.01 is there to prevent the parameter from going negative (negative maize grain orders do not make sense) and to prevent the model from dividing by zero in the "ratio inf retailing not fulfilled" variable.

- $\text{Desired_Informal_grain_storage} = \text{Monthly_demand_informal_original} * \text{CT_informal_grain_storage}$
 UNITS: metric ton
 DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, desired storage is determined by the coverage time and the demand.
- $\text{Desired_Inf_customer_meal_storage} = \text{Monthly_Demand_Informal} * \text{CT_inf_customer_meal_strg}$
 UNITS: metric ton
 DOCUMENT: Following Sterman's (2000: chapter 17-18) classical conceptualization of supply chains, desired storage is determined by the coverage time and the monthly demand.
- $\text{Gap_Demand_Informal} = \text{Monthly_Demand_Informal} - \text{Consumption_Informal}$
 UNITS: metric ton/mo
 DOCUMENT: The gap between demand and the maize actually available for consumption.
- $\text{Gap_informal_meal_storage} = \text{Desired_Inf_customer_meal_storage} - \text{Informal_customer_meal_storage}$
 UNITS: metric ton
- $\text{Gap_inf_customer_grain_storage} = \text{Desired_Informal_grain_storage} - \text{Informal_customer_grain_storage}$
 UNITS: metric ton
- $\text{Inf_demand_to_formal_spillover_adjusted} = \text{Inf_demand_to_formal_spillover_indicative} * \text{Ratio_of_meal_as_grain_substitute}$
 UNITS: metric ton/mo
 DOCUMENT: The amount of demand that spills over into the formal value chain.
- $\text{Inf_demand_to_formal_spillover_indicative} = \text{Gap_Demand_Informal}$
 UNITS: metric ton/mo
 DOCUMENT: The gap in consumption needs to be satisfied so consumers fill up their diet with maize from the formal value chain.
- $\text{Loss_Ratio_Hammer_Milling} = 0.05$
 UNITS: Unitless
 DOCUMENT: There is a 5% loss in the hammer milling of maize process (Keyser, 2007: table 49).
- $\text{Monthly_demand_informal} = \text{Monthly_demand_informal_original} * \text{Effect_of_perc_ratio_on_informal_demand}$
 UNITS: metric ton/mo
 DOCUMENT: Demand for self-milled hammer meal that is adjusted for the consumer response to changes in the availability of maize grain.
- $\text{OR_Hammer_Milling} = \text{DAR_hammer_milling} * (1 + \text{Loss_Ratio_Hammer_Milling})$
 UNITS: metric ton/mo
 DOCUMENT: Since it is likely that consumer roughly know how much grain is being lost in the milling process, I assume that they apply a rule of thumb by ordering those 5% loss ratio on top of what they actually want. The order rate is therefore the DAR + 5%.
- $\text{Ratio_inf_retailing_not_fulfilled} = 1 - \text{Informal_grain_retailing} / \text{DAR_informal_retailing}$
 UNITS: Unitless
 DOCUMENT: Ratio of demand for grain purchases by consumers that is not fulfilled due to supply shortages.
- $\text{Ratio_of_meal_as_grain_substitute} = 0.781$
 UNITS: Unitless
 DOCUMENT: The amount of the demand gap that is not fulfilled with commercial roller meal as a substitute for self-milled hammer meal, but satisfied by changing to other crops. Data taken from: Nicole Mason & Jayne (2009: table 17). Note that I took the data for Lusaka as most representative for urban areas.

Effect_of_perc_ratio_on_informal_demand = GRAPH(Perc_ratio_inf_retailing_not_fulfilled)
 (0.00, 1.00), (0.0526, 1.00), (0.105, 0.998), (0.158, 0.996), (0.211, 0.992), (0.263, 0.989), (0.316, 0.985), (0.368, 0.981), (0.421, 0.976), (0.474, 0.97), (0.526, 0.962), (0.579, 0.953), (0.632, 0.943), (0.684, 0.932), (0.737, 0.918), (0.789, 0.9), (0.842, 0.882), (0.895, 0.858), (0.947, 0.833), (1.00, 0.804)

UNITS: Unitless

DOCUMENT: Relation: $D1 = \text{Recommended Demand} / 0.80398 = \text{Ratio of Minimum Demand of Recommended demand}$, as taken from FAO (2014) This is a price-proxy variable, representing that people reduce their consumption as grain becomes scarce, and therefore also more expensive. However, they would do almost anything to prevent starvation, e.g. selling other assets, so that the lower bound for the consumption reduction is the Minimal Dietay Requirement by FAO (2014). (Nyanga 2015a)

A.4 Side Calculations

Smallholder_maize_carryover_stocks(t) = Smallholder_maize_carryover_stocks(t - dt) + (Chng_in_SH_maize_carryover_stocks - Emptying_SH_maize_carryover_stocks) * dt

INIT Smallholder_maize_carryover_stocks = 0

UNITS: metric ton

DOCUMENT: Initial value of zero because we start late in the lean season in a deficit production year, so that it is unlikely that there are any carryover stocks from 2003 to 2004.

INFLOWS:

Chng_in_SH_maize_carryover_stocks = IF Yearly__counter >= 1 AND Yearly__counter < 1.05 THEN Smallholder_farm_grain_storage / AT_Chng_carry_over_stocks ELSE 0

UNITS: metric ton/mo

DOCUMENT: Every new year, the smallholder carryover stocks are updated. A carryover stock is any maize that is left from last year still in the smallholder's farm storage.

OUTFLOWS:

Emptying_SH_maize_carryover_stocks = IF Yearly__counter >= 12.75 AND Yearly__counter < 130 THEN Smallholder_maize_carryover_stocks / DT ELSE 0

UNITS: metric ton/mo

DOCUMENT: This flow's purpose is to empty the carryover stock at the end of every year, so that the new stock can be updated at the beginning of the following year.

Total_yearly_comm_sales_smallholder(t) = Total_yearly_comm_sales_smallholder(t - dt) + (Chng_in_total_yr_comm_sales_smallholder - Emptying_total_yr_comm_sales_smallholder) * dt

INIT Total_yearly_comm_sales_smallholder = 0

UNITS: metric ton

DOCUMENT: This stock represents the accumulated purchases from smallholders by non-FRA buyers over the year.

INFLOWS:

Chng_in_total_yr_comm_sales_smallholder = Commercial_maize_assemblage + Informal_grain_retailing

UNITS: metric ton/mo

DOCUMENT: This flow accumulates the sales from smallholder farmers by non-FRA actors over the year.

OUTFLOWS:



Emptying_total_yr_comm_sales_smallholder = IF Yearly__counter >= 12.75 AND Yearly__counter <= 130 THEN Total_yearly_comm_sales_smallholder / DT ELSE 0

UNITS: metric ton

DOCUMENT: This flow's purpose is to empty the "total yearly comm sales smallholder" stock at the end of every year, so that the new stock can be updated at the beginning of the following year.


- $Total_yearly_loss_SH_farm_storage(t) = Total_yearly_loss_SH_farm_storage(t - dt) + (Chng_in_total_yearly_SH_farm_storage_loss - Emptying_total_yearly_farm_storage_loss) * dt$
 INIT $Total_yearly_loss_SH_farm_storage = 0$
 UNITS: metric ton
 DOCUMENT: This stock represents the accumulated maize losses in the smallholder farm storage over the year.
 INFLOWS:
 ☞ $Chng_in_total_yearly_SH_farm_storage_loss = SH_farm_storage_loss$
 UNITS: metric ton/mo
 DOCUMENT: This flow accumulates the losses in the smallholder storage over the year.
 OUTFLOWS:
 ☞ $Emptying_total_yearly_farm_storage_loss = IF\ Yearly_counter \geq 12.75\ AND\ Yearly_counter < 130\ THEN\ Total_yearly_loss_SH_farm_storage / DT\ ELSE\ 0$
 UNITS: metric ton/mo
 DOCUMENT: This flow's purpose is to empty the "total yearly loss SH farm storage" stock at the end of every year, so that the new stock can be updated at the beginning of the following year.
- $Total_yearly_smallholder_production(t) = Total_yearly_smallholder_production(t - dt) + (Chng_in_total_SH_yearly_production - Emptying_total_yearly_SH_production) * dt$
 INIT $Total_yearly_smallholder_production = 0$
 UNITS: metric ton
 DOCUMENT: This stock is the accumulation of all smallholder harvest that was collected in a given year. The initial value is zero because the harvest in 2004 starts coming in not before March.
 INFLOWS:
 ☞ $Chng_in_total_SH_yearly_production = Smallholder_surplus_green_harvest + Smallholder_surplus_main_harvest + SH_subsistence_green_harvest + SH_subsistence_main_harvest$
 UNITS: metric ton/mo
 DOCUMENT: This flow accumulates all the smallholder harvest collected in a given year.
 OUTFLOWS:
 ☞ $Emptying_total_yearly_SH_production = IF\ Yearly_counter \geq 2.5\ AND\ Yearly_counter < 30\ THEN\ Total_yearly_smallholder_production / DT\ ELSE\ 0$
 UNITS: metric ton/mo
 DOCUMENT: This flow's purpose is to empty the "total yearly smallholder production" stock at the end of every marketing year just before the new harvest comes in, so that the new stock can be updated at the beginning of the following year.
- $ADESM = Total_monthly_consumption / (Monthly_non_subsistence_demand - Demand_changing_to_other_crops)$
 UNITS: Unitless
 DOCUMENT: As described in chapter 3.4, the ADESM is calculated as: $Maize\ consumption / Adjusted\ maize\ demand$
- $AT_Chng_carry_over_stocks = 0.05$
 UNITS: months (mo)
 DOCUMENT: The time horizon over which the carryover stock is updated. It is kept very short so that the difference between the updated carryover stock and the value of the "smallholder farm grain storage" is as small as possible in case that the farm storage is subject to change in the updating time.

- $Available_SH_purchase_volume_commercial = Smallholder_maize_carryover_stocks + Yearly_SH_surplus_production - Total_yearly_loss_SH_farm_storage - FRA_domestic_yearly_purchase$
 UNITS: metric ton/year
 DOCUMENT: The total amount of maize that is available for non-FRA (commercial) buyers to purchase from smallholders in the current year equals the smallholder surplus maize stocks that were carried over from last year plus the yearly production for the current year. From that, we need to deduct the amount of purchases that FRA contracts with the farmers, as well as the losses. For more details, see chapter 4.6.3
- $Changes_in_the_switch_per_year = 1$
 UNITS: per year (1/yr)
 DOCUMENT: This variable represents how often the switch is changed in a given year - only once.
- $Demand_changing_to_other_crops = Inf_demand_to_formal_spillover_indicative - Inf_demand_to_formal_spillover_adjusted$
 UNITS: metric ton/mo
 DOCUMENT: The difference between the indicative demand spillover (which equals the gap in consumption in the informal value chain) and the actual demand that spills over from the informal into the formal value chain is the amount of demand that consumers satisfy by changing to consuming other crops. This demand therefore can no longer be counted into the demand for maize.
- $Ratio_maize_in_sheds_FRA = IF\ FRA_maize_in_permanent_storage \geq 10\ THEN\ MAX(0, FRA_maize_in_permanent_storage - FRA_Silo_capacity) / FRA_maize_in_permanent_storage\ ELSE\ 0$
 UNITS: Unitless
 DOCUMENT: Assuming that they fill up the silos first whenever possible (due to the much lower losses) and only bring/leave the leftovers in the sheds. MAX function so there will be no negative values in case there is less maize in store than there silo capacity (meaning: silos are not full) IF function to prevent the division by zero in cases of no inventory
- $Ratio_of_sheds_in_FRA_capacity = Shed_capacity_FRA / Total_built_capacity_FRA$
 UNITS: Unitless
- $Switch_comm_farmers_exports = IF\ Total_yearly_smallholder_production > Total_yearly_maize_demand * 1.15\ THEN\ 1\ ELSE\ 0$
 UNITS: Unitless
 DOCUMENT: Represents the decisions of the Zambian government to lift exports bans for the commercial farmers only when there has been sufficient smallholder production to meet the domestic demand. The markup of 15% is to account for losses in the value chain.
- $Switch_FRA_reserves = IF\ (Yearly_SH_surplus_production + Yearly_commercial_Production) < Yearly_non_subsistence_demand * 1.2\ THEN\ 0\ ELSE\ 1$
 UNITS: Unitless
 DOCUMENT: This switch represents the decision of FRA to offload their desired storage when maize is scarce in Zambia. Since FRA's primary mandate is to ensure a stable maize supply for the Zambian population, then keeping maize locked up in times of national scarcity would neither make sense, nor would it be politically feasible to do so. The mark-up of 20% is to represent a rule-of-thumb of the decision makers to account for losses in the value chain and the FRA storage.
- $Switch_non_FRA_smallholder_sales = IF\ Available_SH_purchase_volume_commercial * Changes_in_the_switch_per_year - Total_yearly_comm_sales_smallholder > 0\ THEN\ 1\ ELSE\ 0$
 UNITS: Unitless
 DOCUMENT: This switch compares the amount of maize that is available for non-FRA buyers to purchase from smallholders to the amount that they have already purchased. When the actual accumulated purchases reach the ceiling of the total available amount, the switch turns to zero, prohibiting any further purchases from smallholders by non-FRA buyers. For a detailed explanation, see chapter 4.6.3.
- $Total_built_capacity_FRA = FRA_Silo_capacity + Shed_capacity_FRA$
 UNITS: metric ton

- Total_monthly_consumption = Consumption_Formal+Consumption_Informal
UNITS: metric ton/mo
- ⊗ FRA_Silo_capacity = GRAPH(TIME)
 (7.00, 55720), (19.0, 55720), (31.0, 55270), (43.0, 55060), (55.0, 54960), (67.0, 54930), (79.0, 54930), (91.0, 57370), (103, 63540), (115, 71920), (127, 82460), (139, 99130), (151, 125610), (163, 164140), (175, 212660), (187, 244410), (199, 248011), (204, 248011)
UNITS: metric ton
DOCUMENT: Data sources: see appendix C.2
- ⊗ Shed_capacity_FRA = GRAPH(TIME)
 (7.00, 539200), (19.0, 567020), (31.0, 566430), (43.0, 566410), (55.0, 566460), (67.0, 566480), (79.0, 566480), (91.0, 590950), (103, 652990), (115, 737320), (127, 833910), (139, 932780), (151, 1e+06), (163, 1.1e+06), (175, 1.2e+06), (187, 1.2e+06), (199, 1.2e+06), (204, 1.2e+06)
UNITS: metric ton
DOCUMENT: Data sources: see appendix C.2

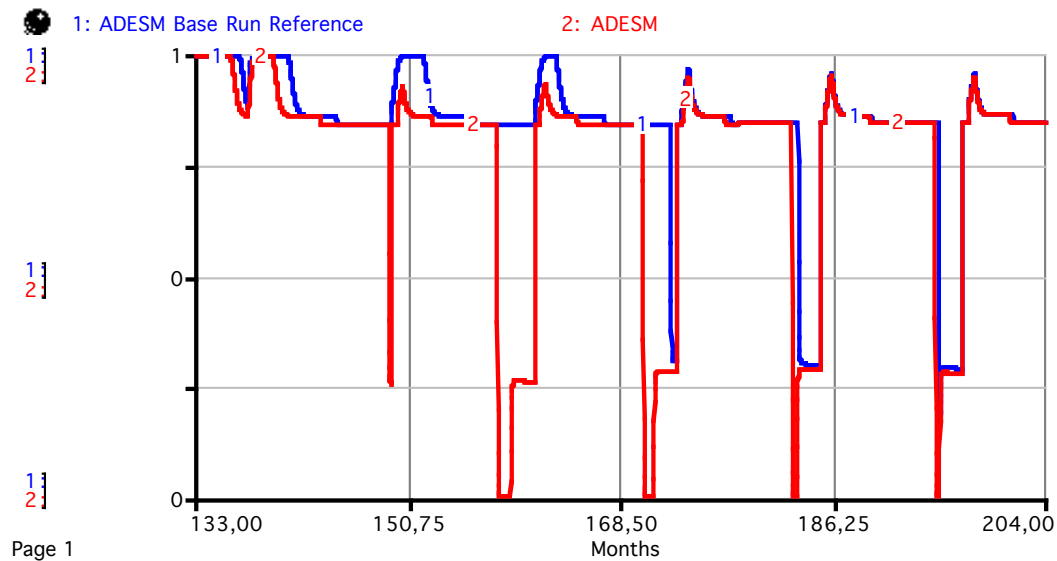
A.5 Subsistence Sector

Subsistence Sector

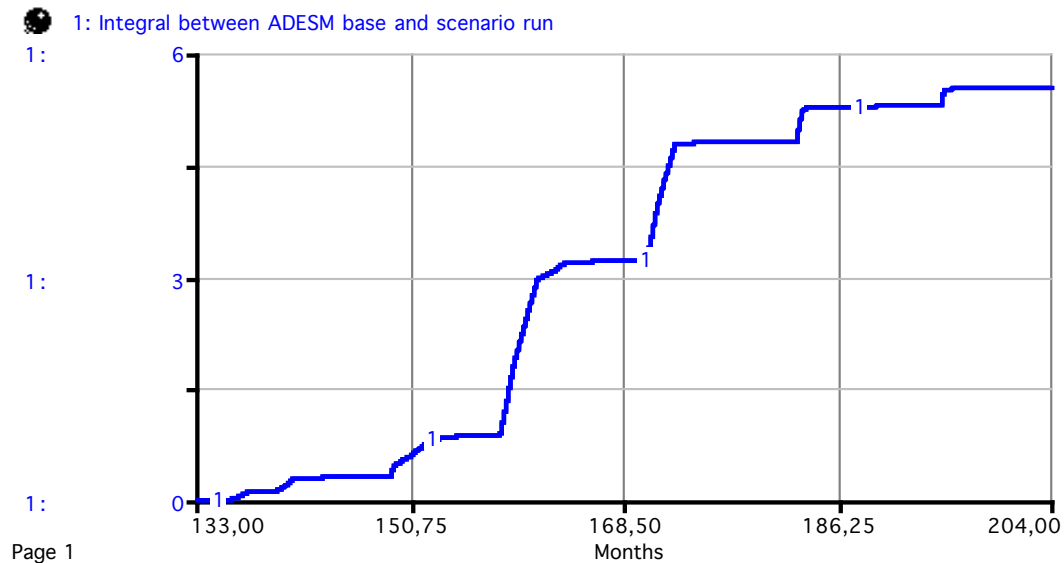
- SH_subsistence_main_harvest = IF Yearly__counter >=5 AND Yearly__counter<7 THEN Yearly_subsistence_Production*Ratio_main_harvest/Main_harvest_months_per_yearELSE 0
UNITS: metric ton/mo
- SH_subsistence_green_harvest = IF Yearly__counter >=3 AND Yearly__counter<5 THEN Yearly_subsistence_Production*(1-Ratio_main_harvest)/Green_harvest_months_per_yearELSE 0
UNITS: metric ton/mo
- ⊗ Yearly_subsistence_Production = GRAPH(TIME)
 (1.00, 821142), (13.0, 621771), (25.0, 775131), (37.0, 621196), (49.0, 603955), (61.0, 1e+06), (73.0, 1.4e+06), (85.0, 1.1e+06), (97.0, 1.3e+06), (109, 1.1e+06), (121, 1.5e+06), (133, 993758), (145, 1e+06), (157, 1e+06), (169, 1.1e+06), (181, 1.1e+06), (193, 1.1e+06), (204, 1.1e+06)
UNITS: metric ton/year
DOCUMENT: Total yearly amount of maize that is produced and consumed by smallholder maize farmers in Zambia for subsistence purposes, and thus never enters the market. Data sources: see appendix C.1

Appendix B: Output Scenario Runs

Scenario 1: Permanent Increase in Kwacha Value Towards US Dollar by 35%

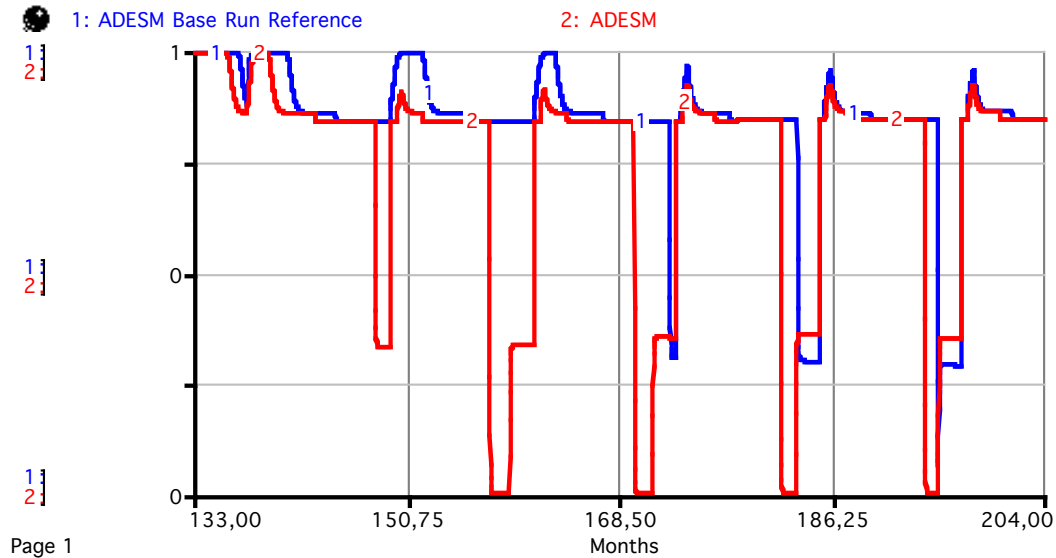


? Comparison ADESM scenario run to base run



? Integral between ADESM for base and scenario run

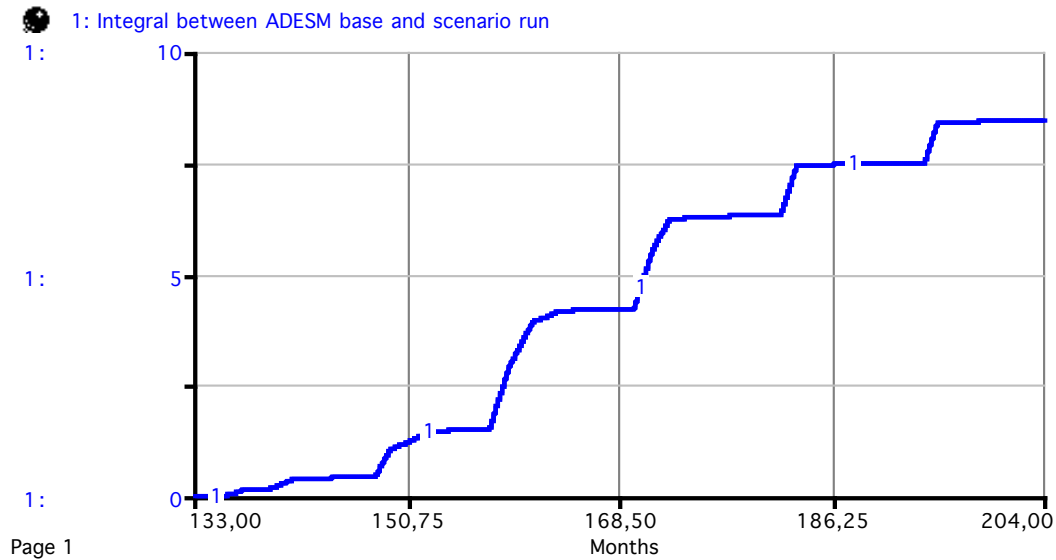
Scenario 2: Permanent Increase Kwacha Value Towards US Dollar by 50%



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Comparison ADESM scenario run to base run

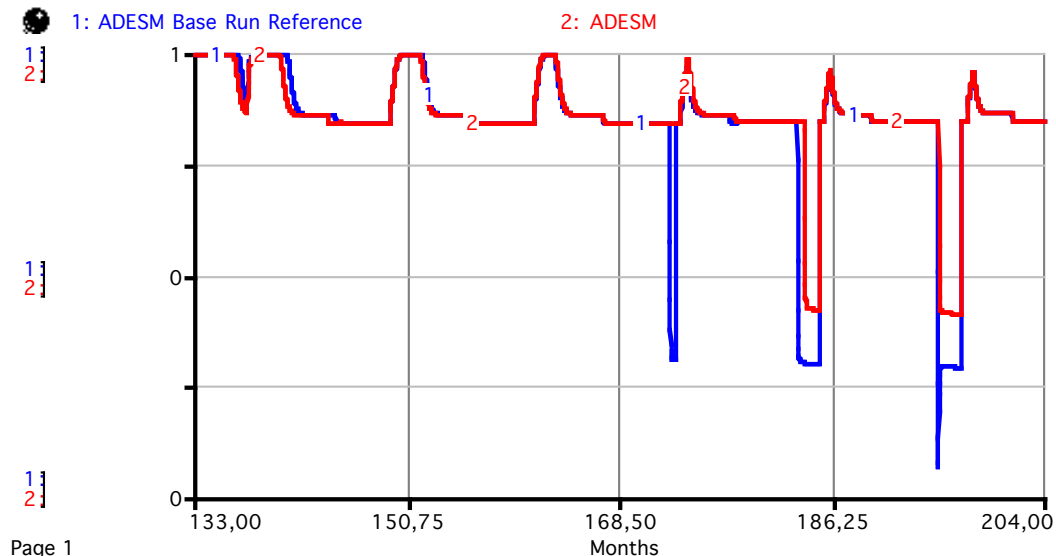


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Integral between ADESM for base and scenario run

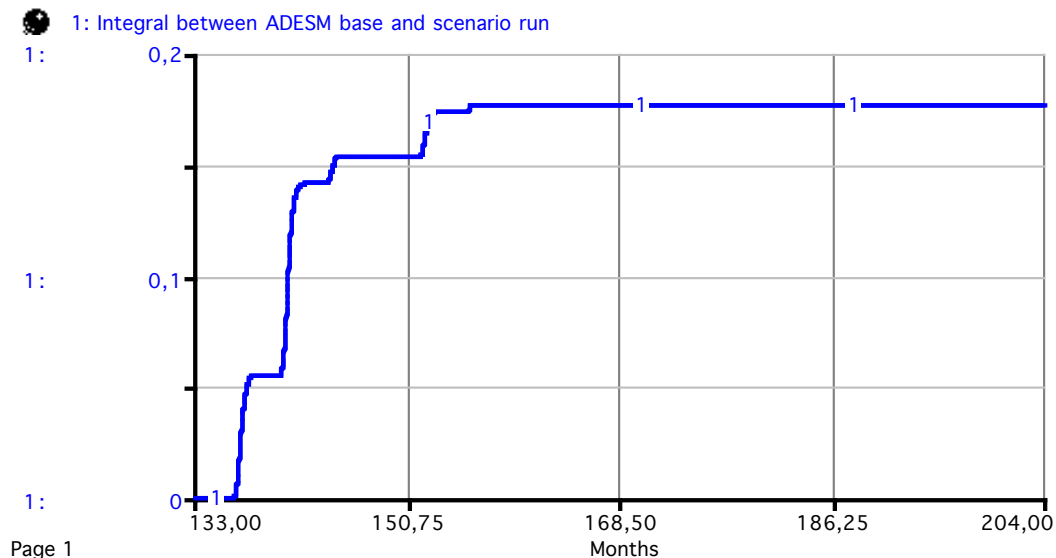
Scenario 3: Flood Loss of Cultivated Area by 10% in 2015



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Comparison ADESM scenario run to base run

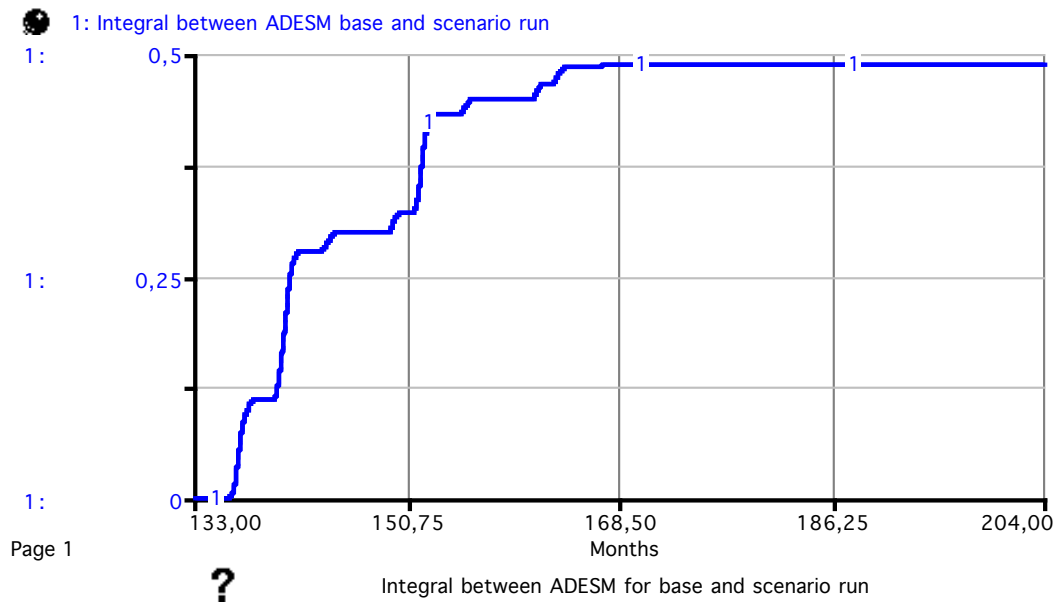
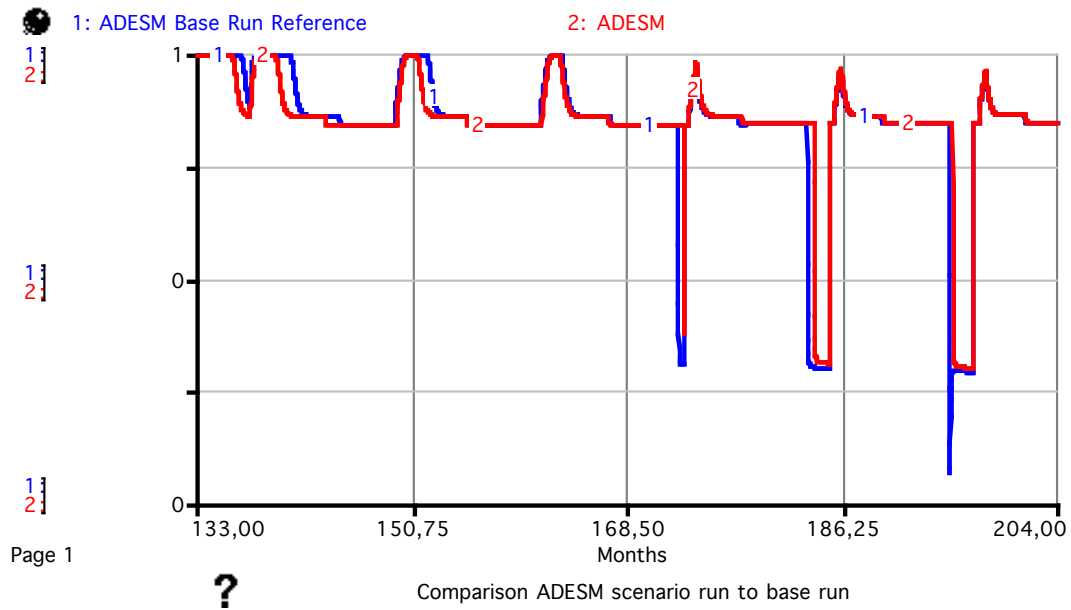


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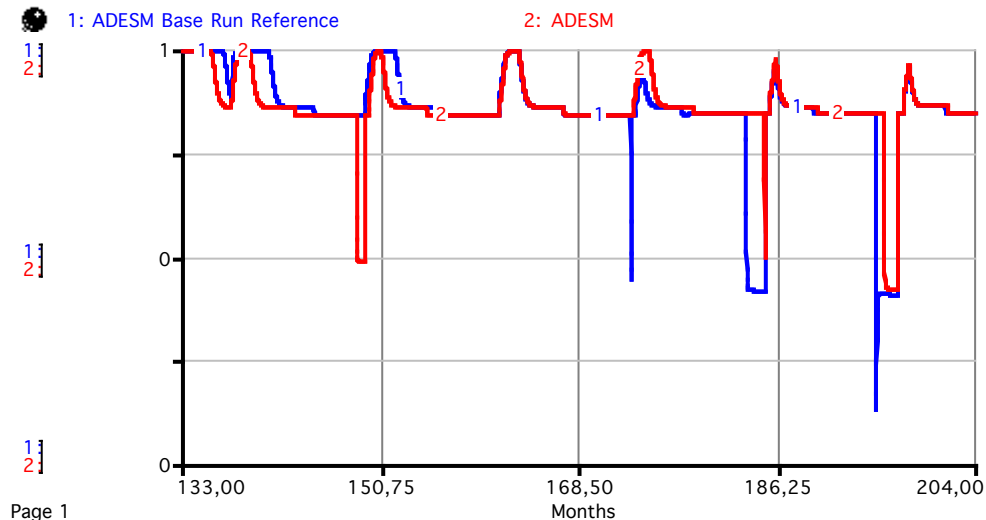
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Integral between ADESM for base and scenario run

Scenario 4: Flood Loss of Cultivated Area by 20% in 2015

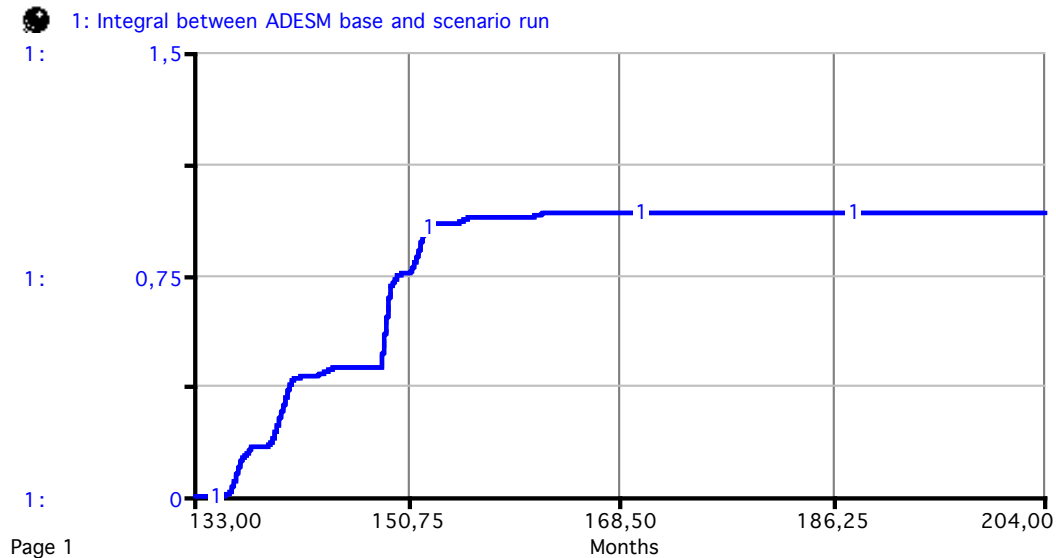


Scenario 5: Flood Loss of Cultivated Area by 30% in 2015



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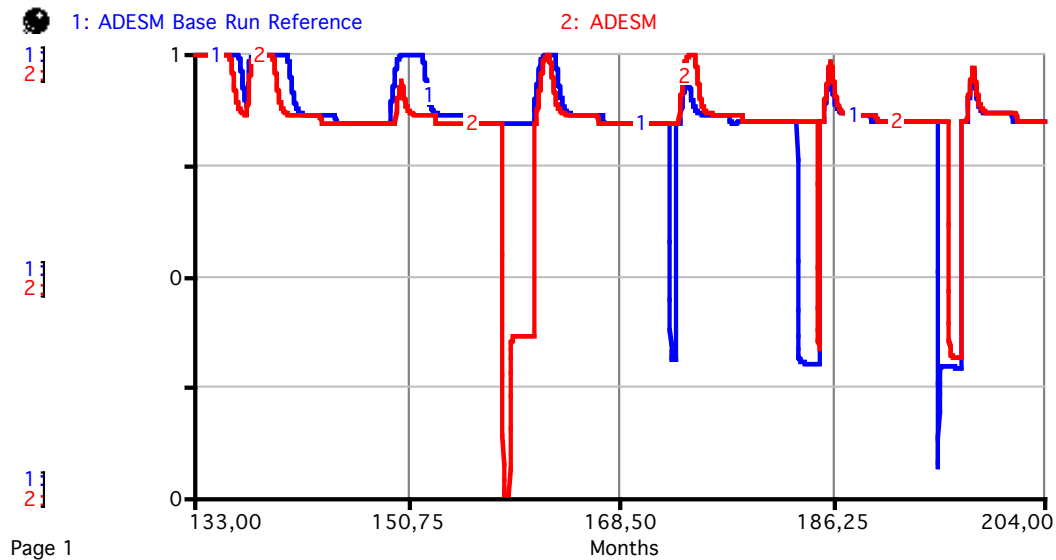
? Comparison ADESM scenario run to base run



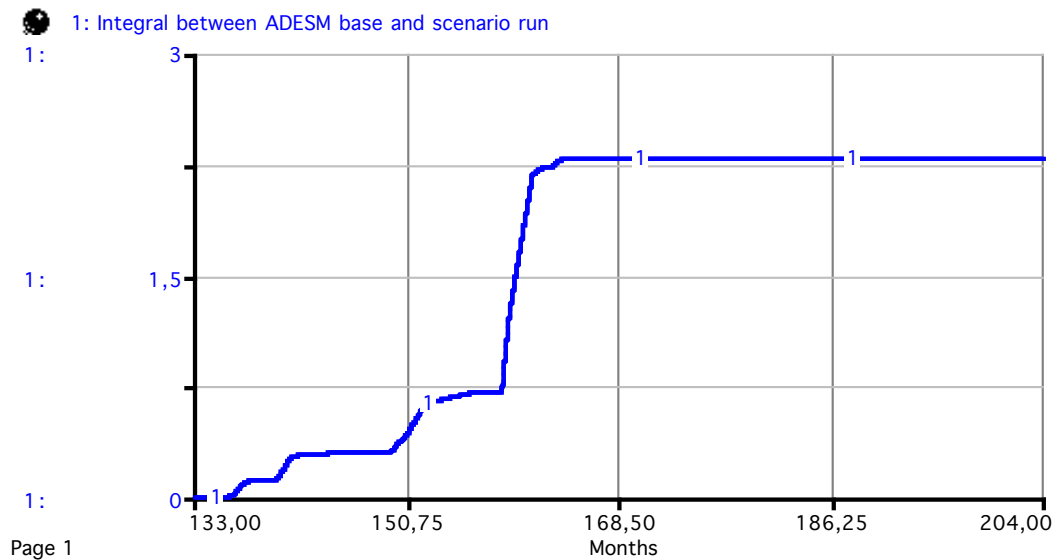
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? Integral between ADESM for base and scenario run

Scenario 6: Flood Loss of Cultivated Area by 20% in two consecutive years (2015-16)

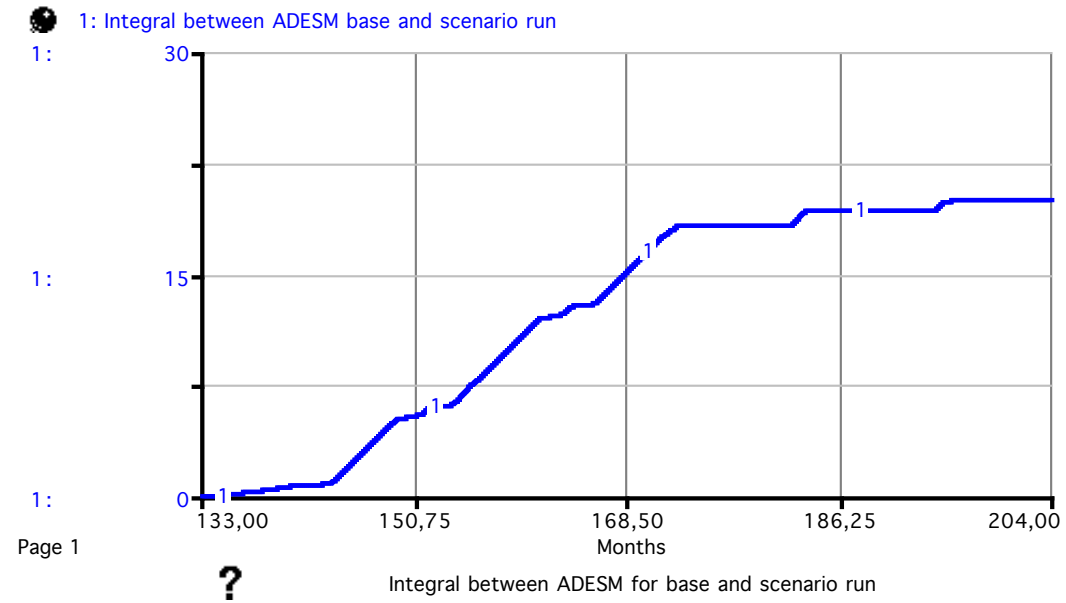
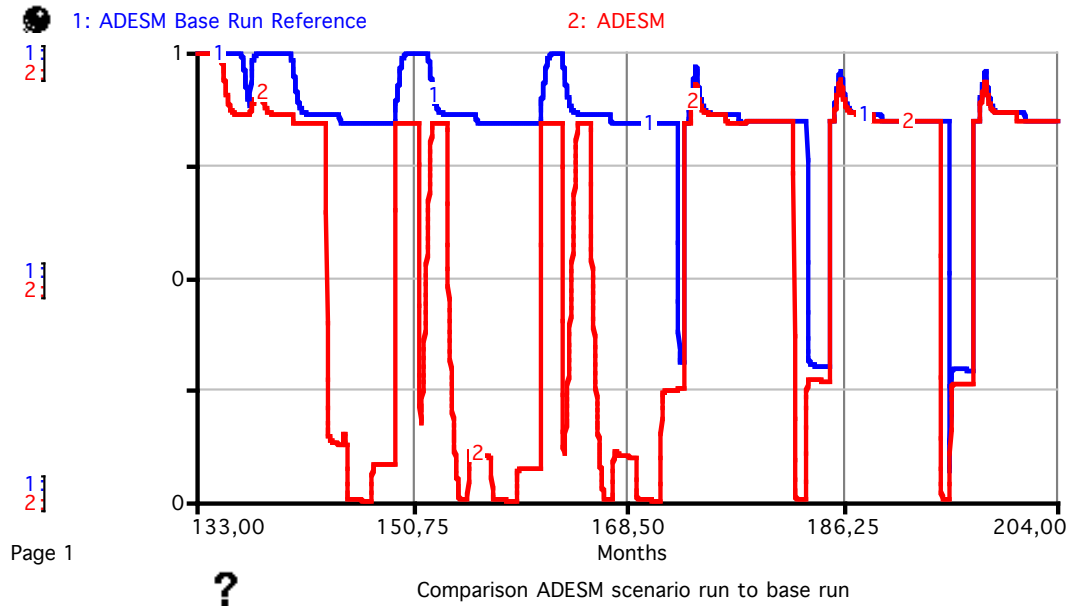


? Comparison ADESM scenario run to base run

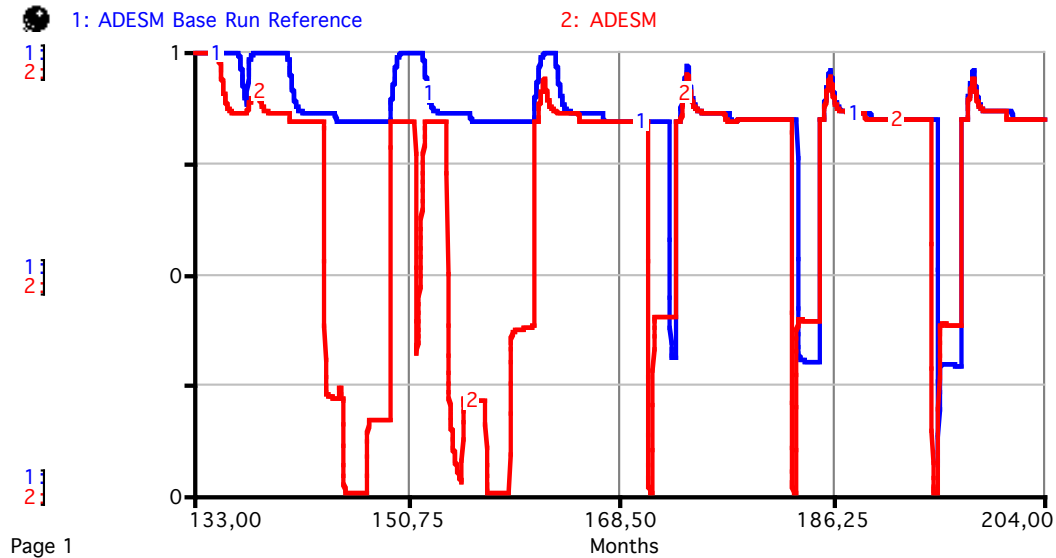


? Integral between ADESM for base and scenario run

Scenario 7: Extreme 3-year Drought (2015-17)



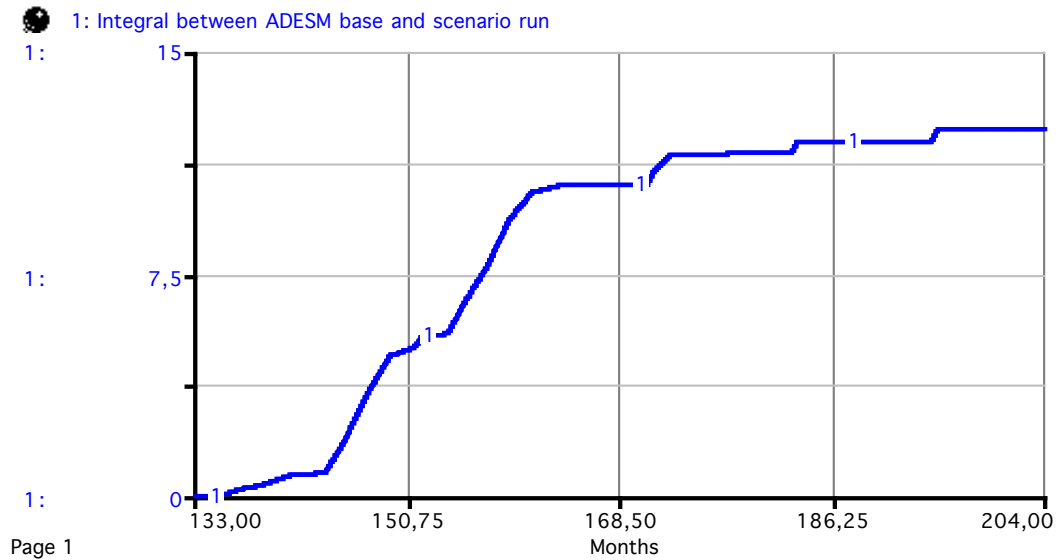
Scenario 8: Extreme 2-year Drought (2015-16)



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Comparison ADESM scenario run to base run

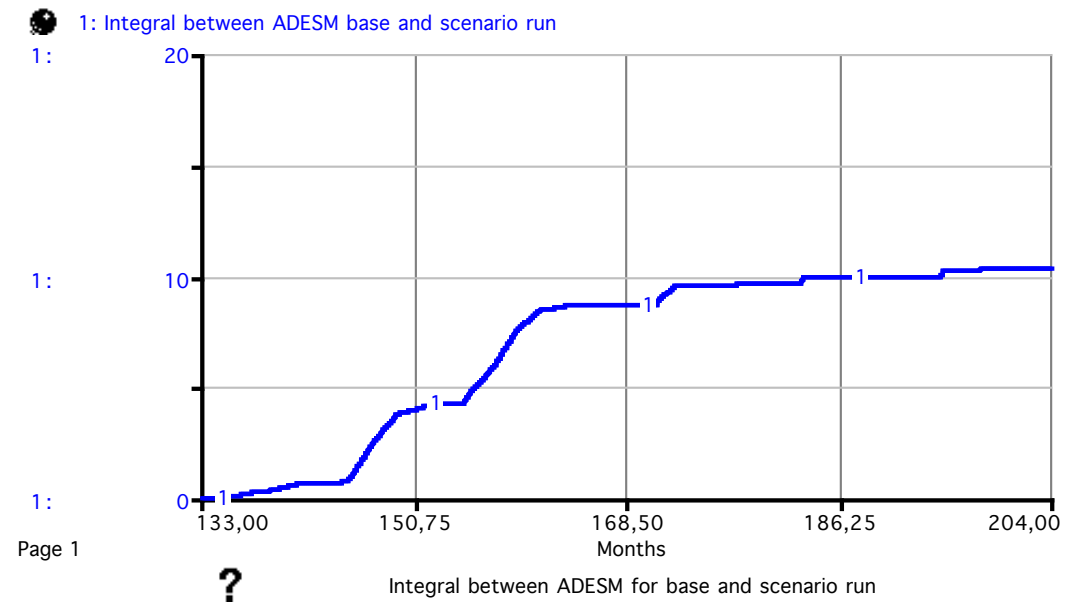
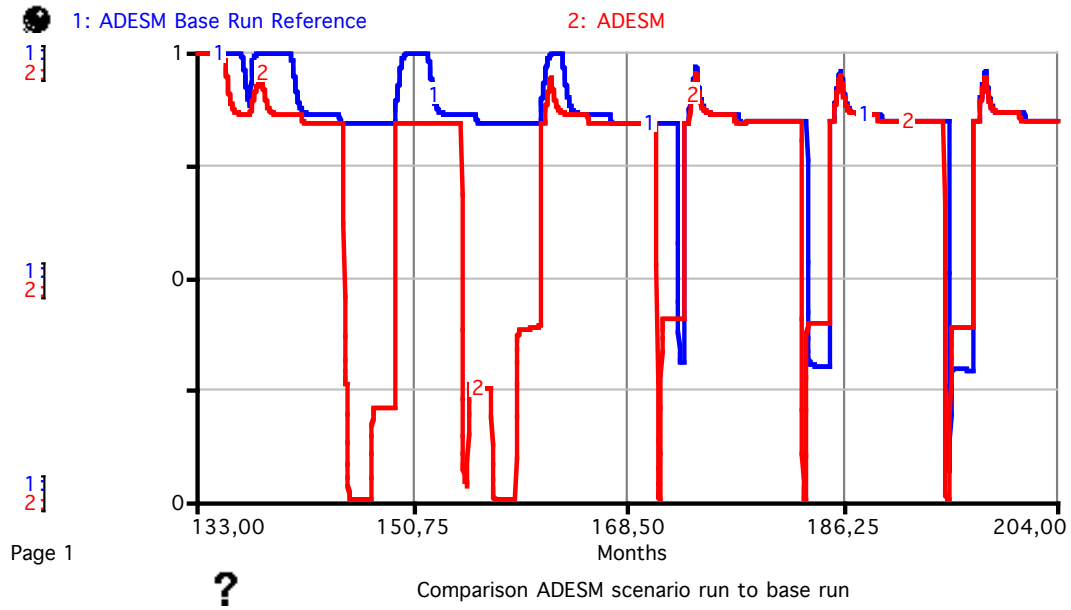


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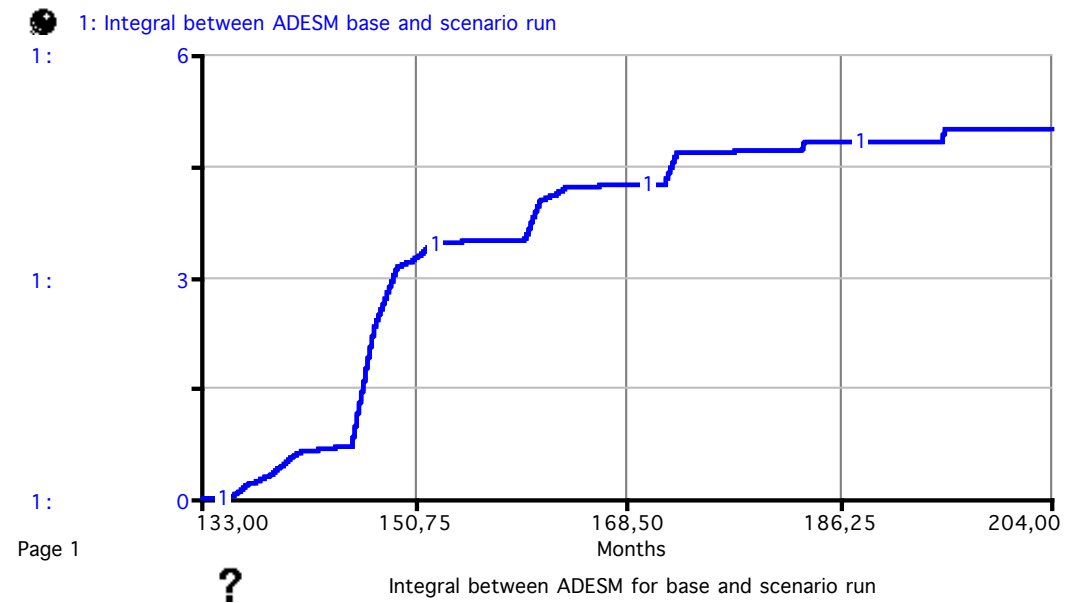
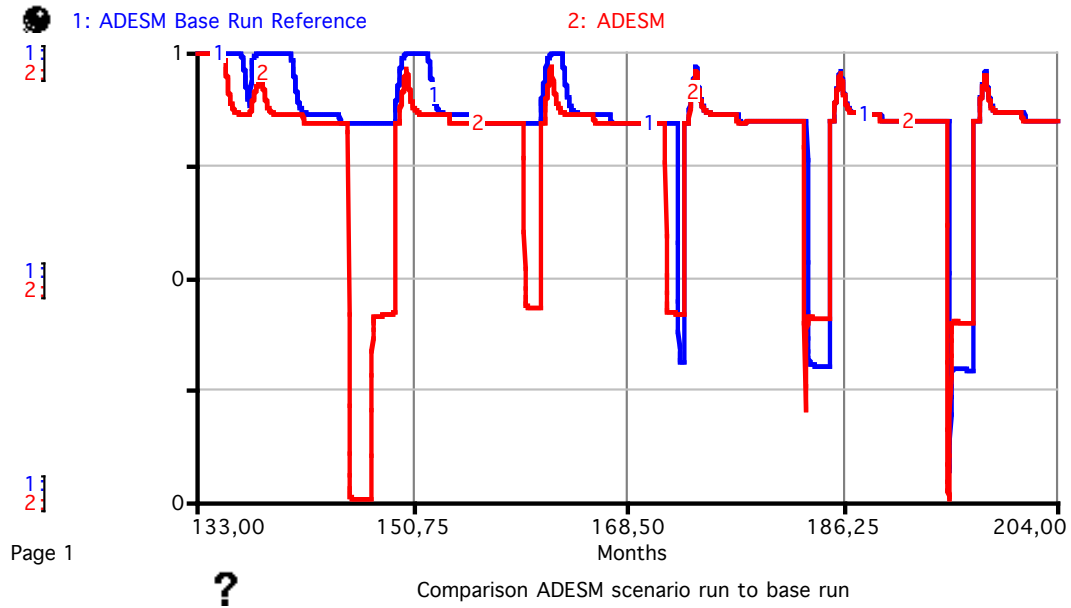
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Integral between ADESM for base and scenario run

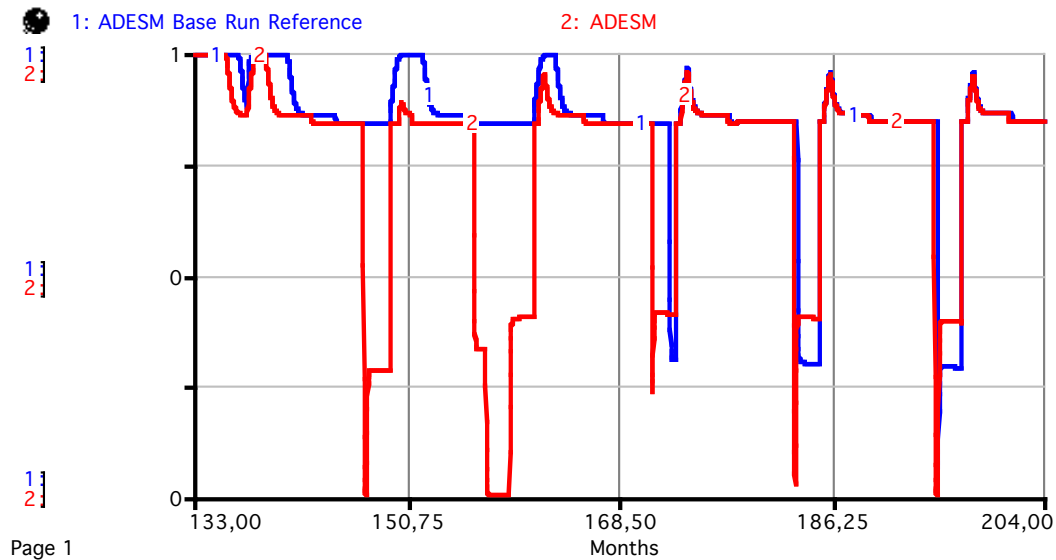
Scenario 10: Severe 2-year Drought (2015-16)



Scenario 11: Severe 1-year Drought (2015)



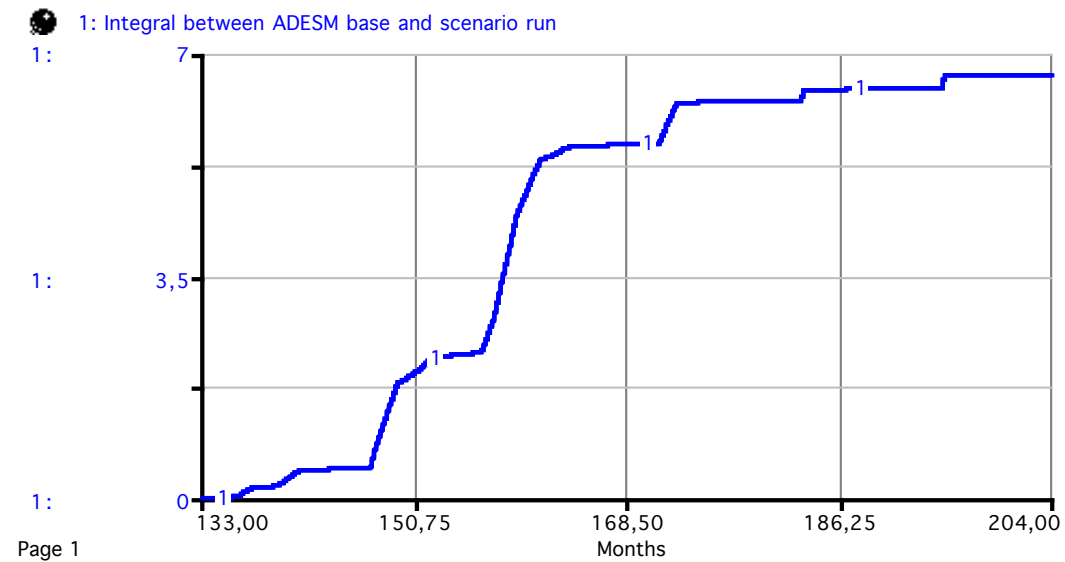
Scenario 12: Moderate 2-year Drought (2015-16)



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Comparison ADESM scenario run to base run

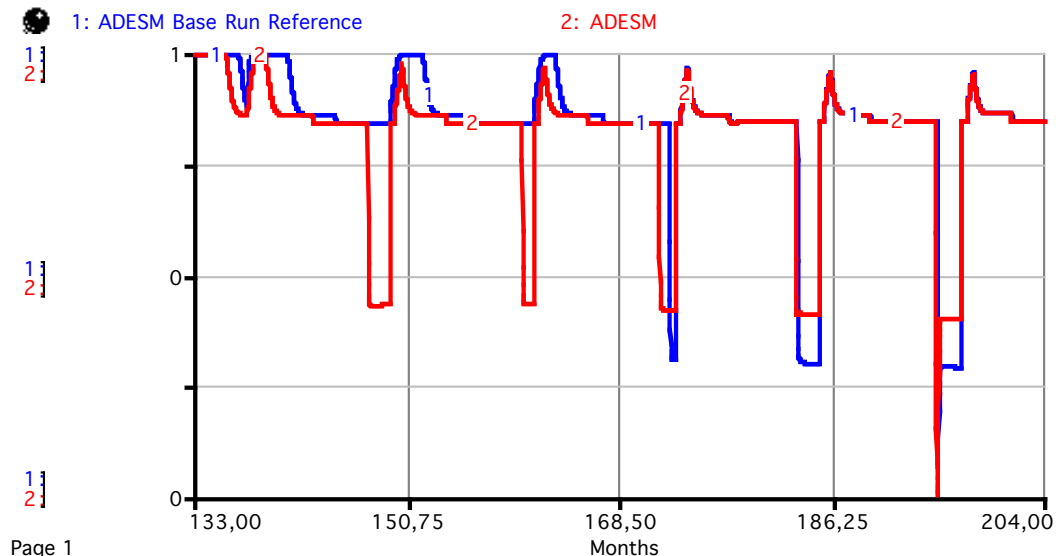


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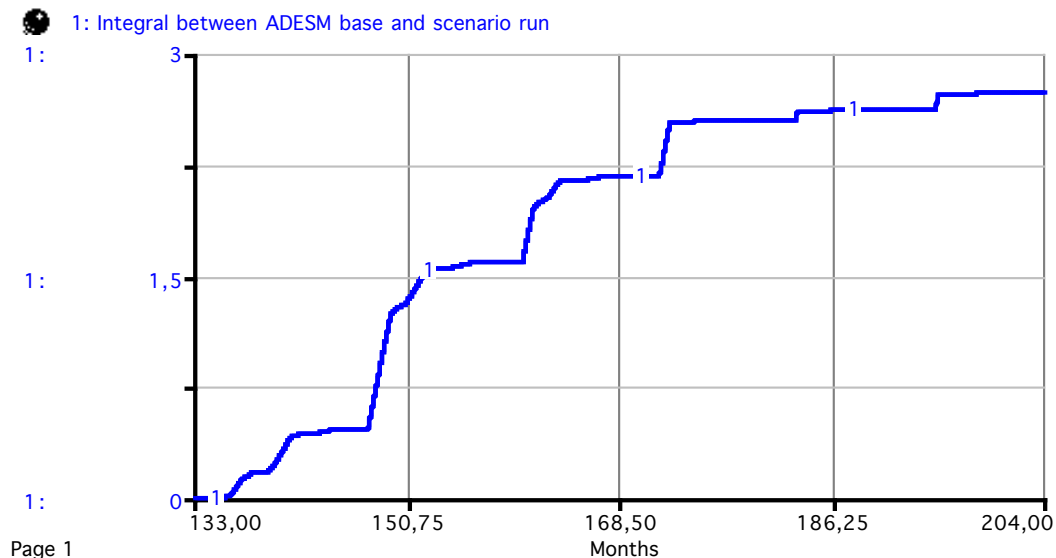
Integral between ADESM for base and scenario run

Scenario 13: Moderate 1-year Drought (2015)



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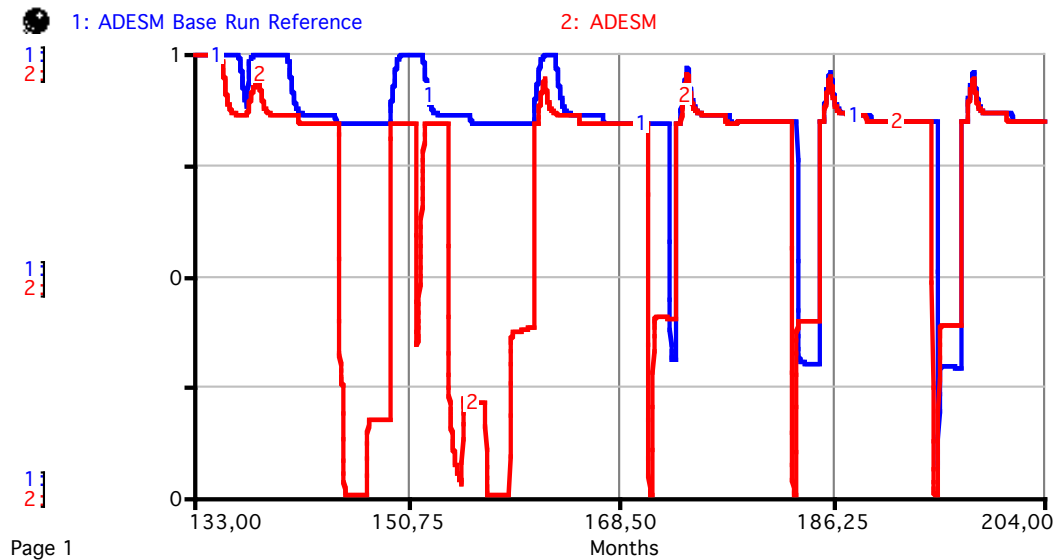
? Comparison ADESM scenario run to base run



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? Integral between ADESM for base and scenario run

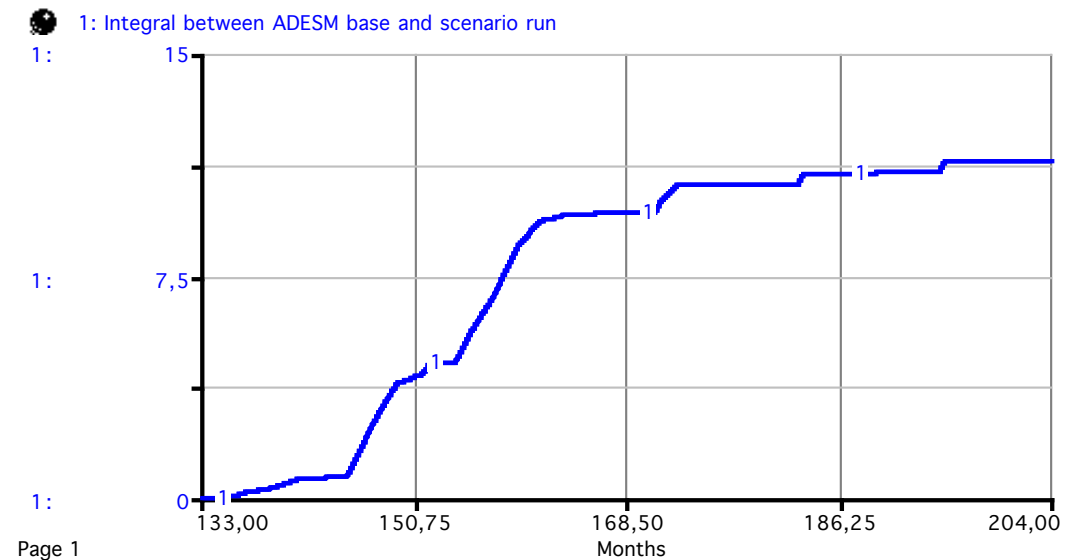
Scenario 14: Extreme followed by Severe Drought (2015-16)



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Comparison ADESM scenario run to base run

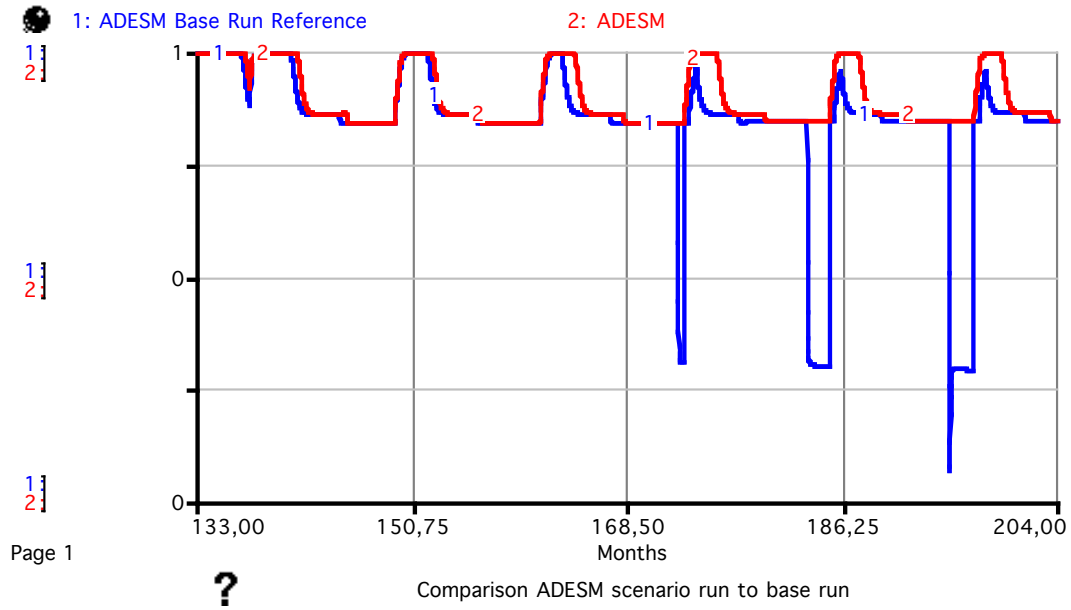


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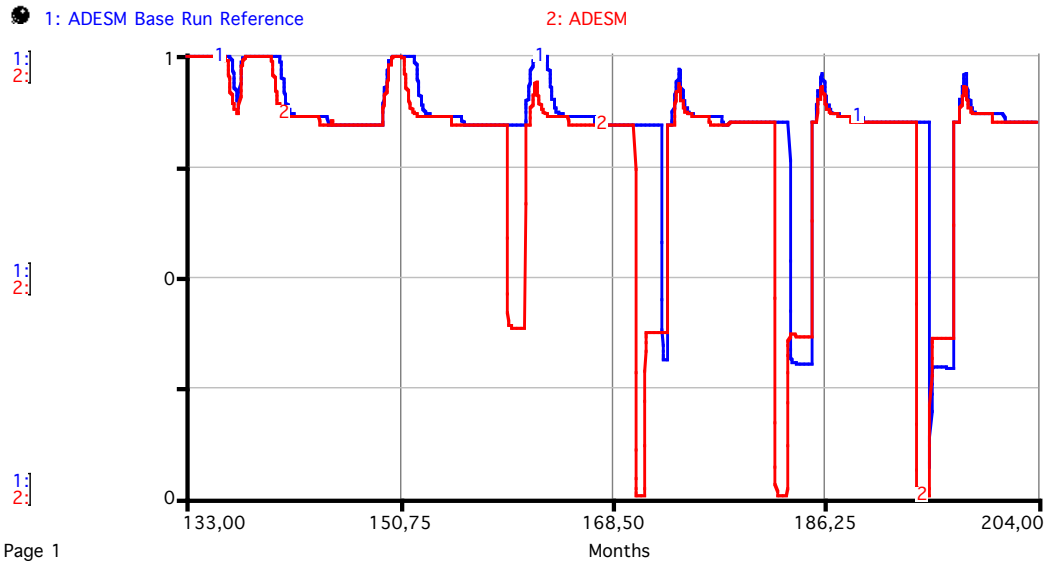
Integral between ADESM for base and scenario run

Scenario 15: Steady Fertilizer Subsidies of 1500 Kwacha/Person/Year



This is not a shock scenario: the performance of the production sector, and thus the trajectory of the ADESM, become even better in comparison to the base run where subsidies are assumed to not increase with the population, but stay on a steady total level.

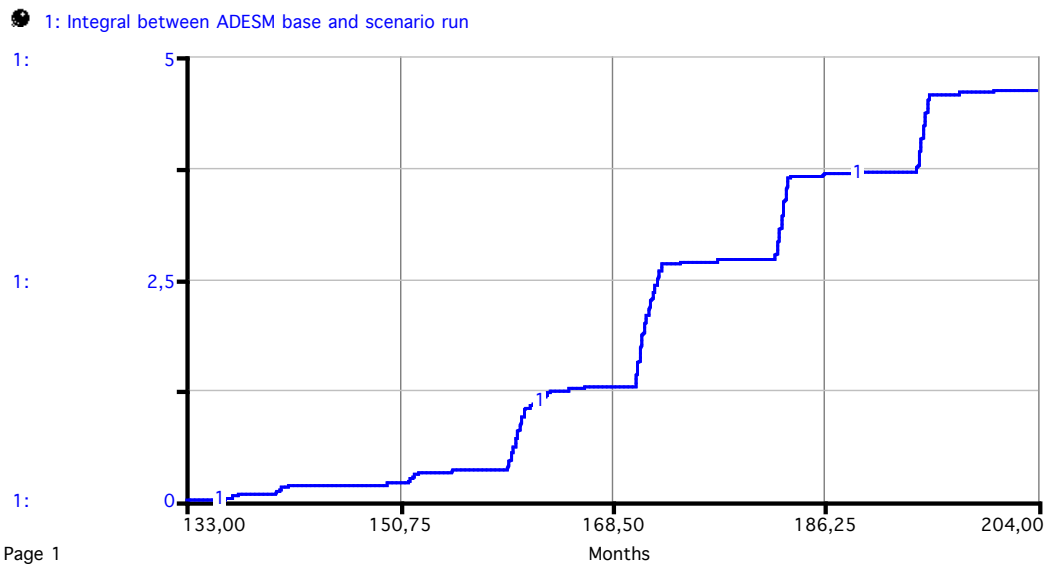
Scenario 16: Fertilizer Subsidies Permanently Cut in Half to 750 Kwacha per Person and Year



Page 1

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Comparison ADESM scenario run to base run

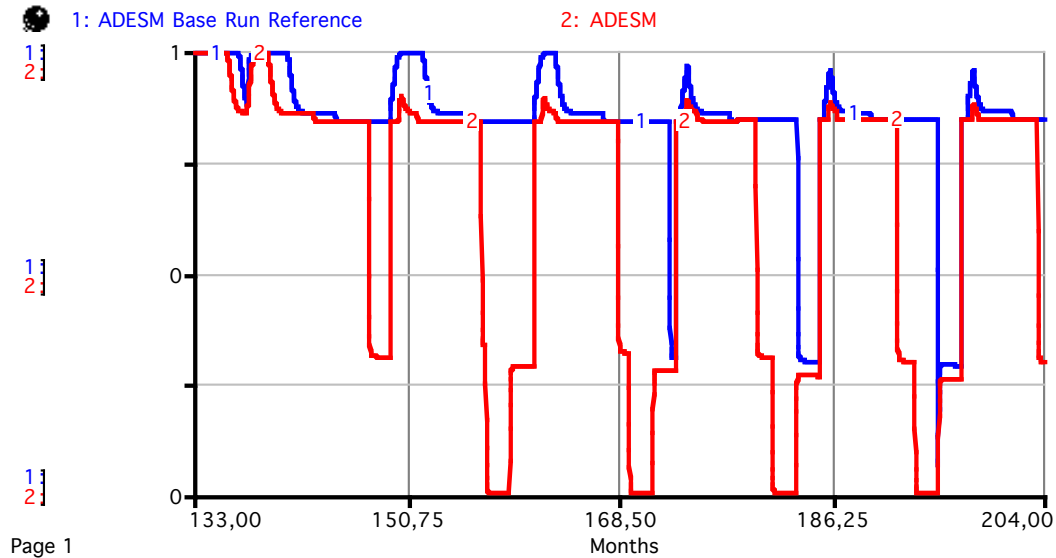


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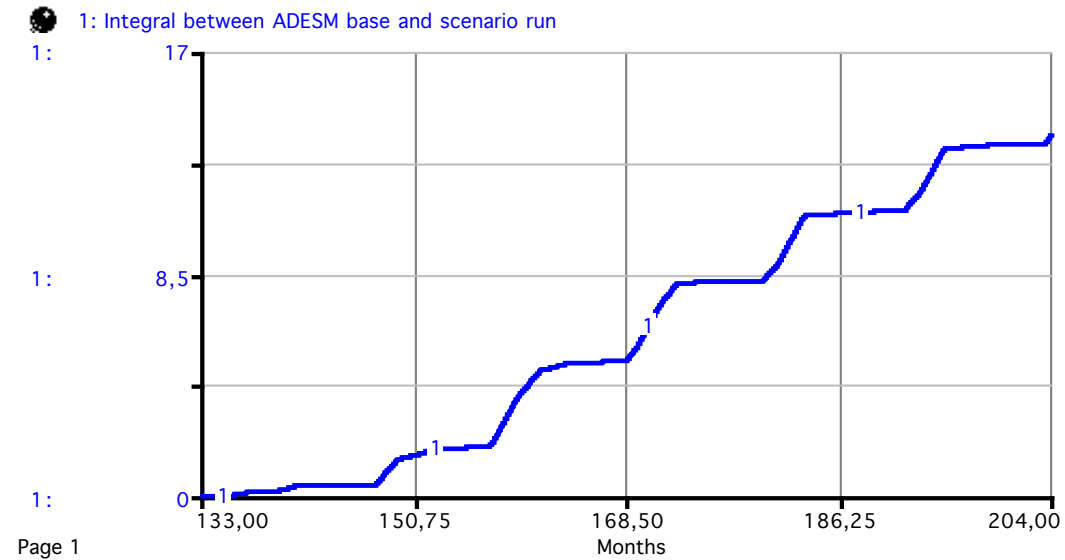
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Integral between ADESM for base and scenario run

Scenario 17: Fertilizer Subsidies Permanently Abandoned

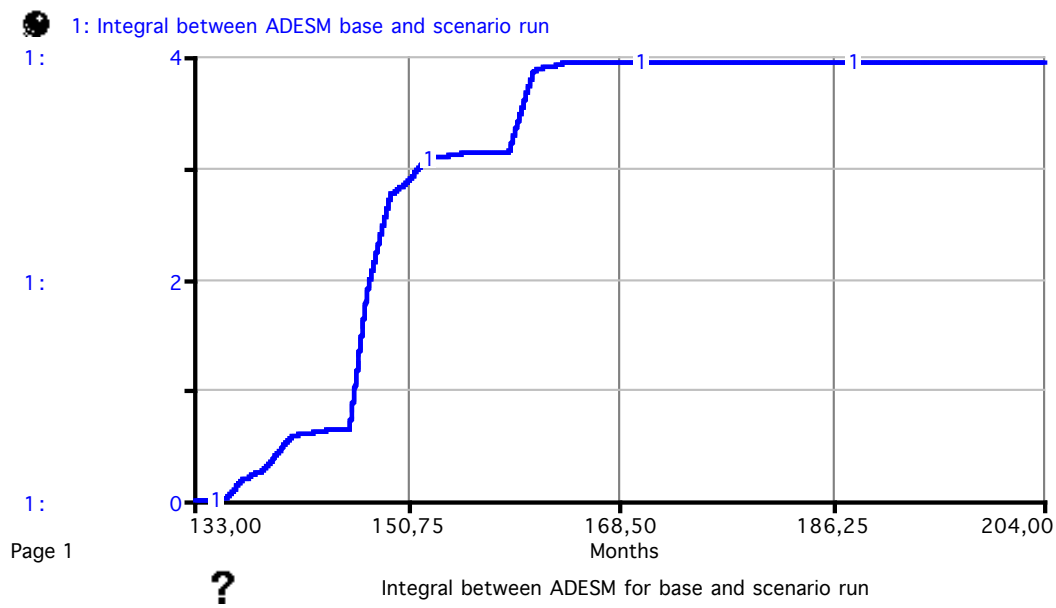
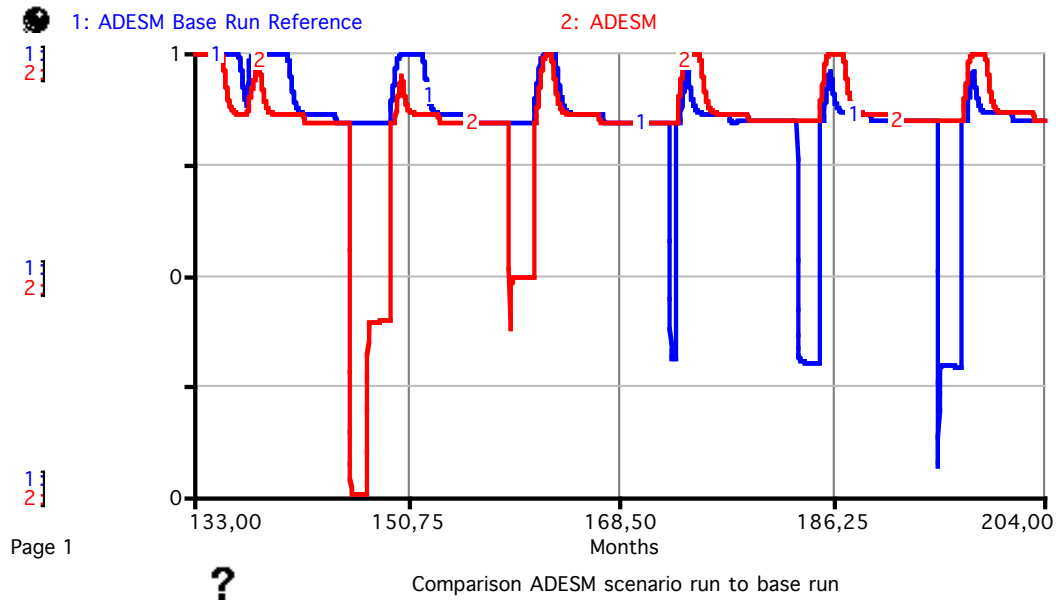


? Comparison ADESM scenario run to base run

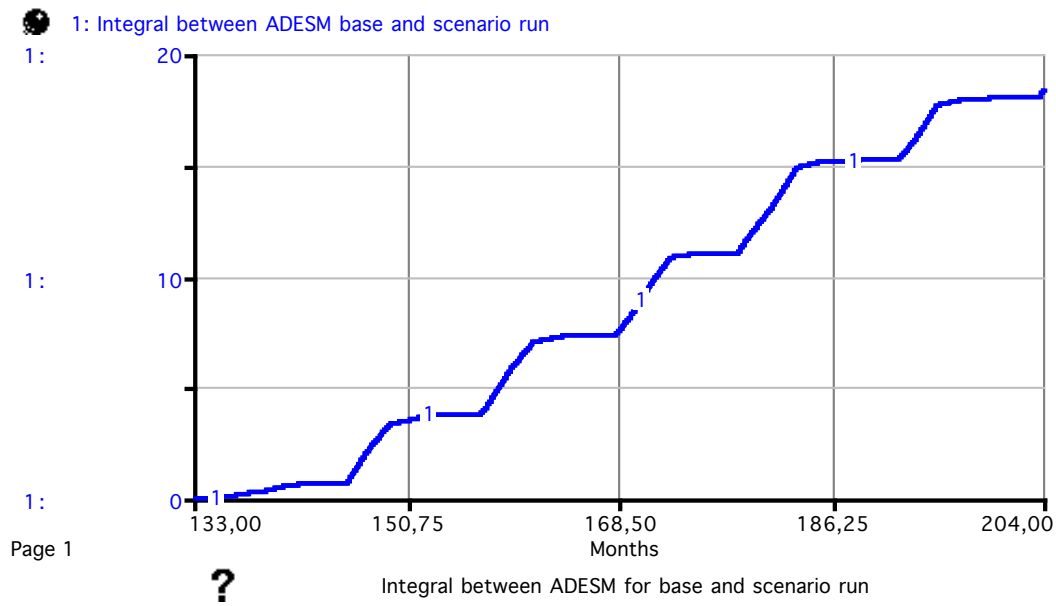
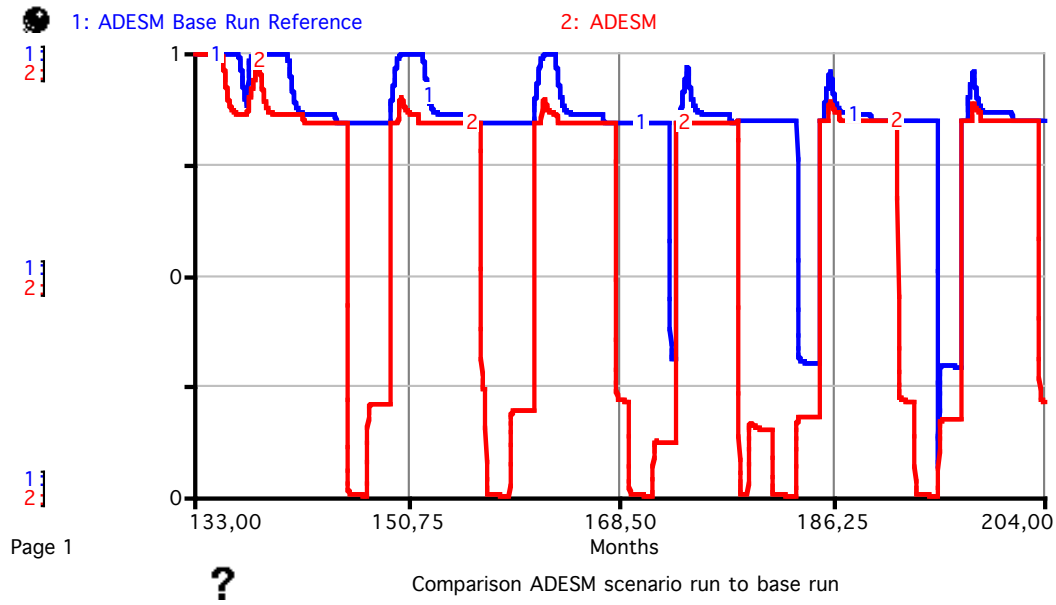


? Integral between ADESM for base and scenario run

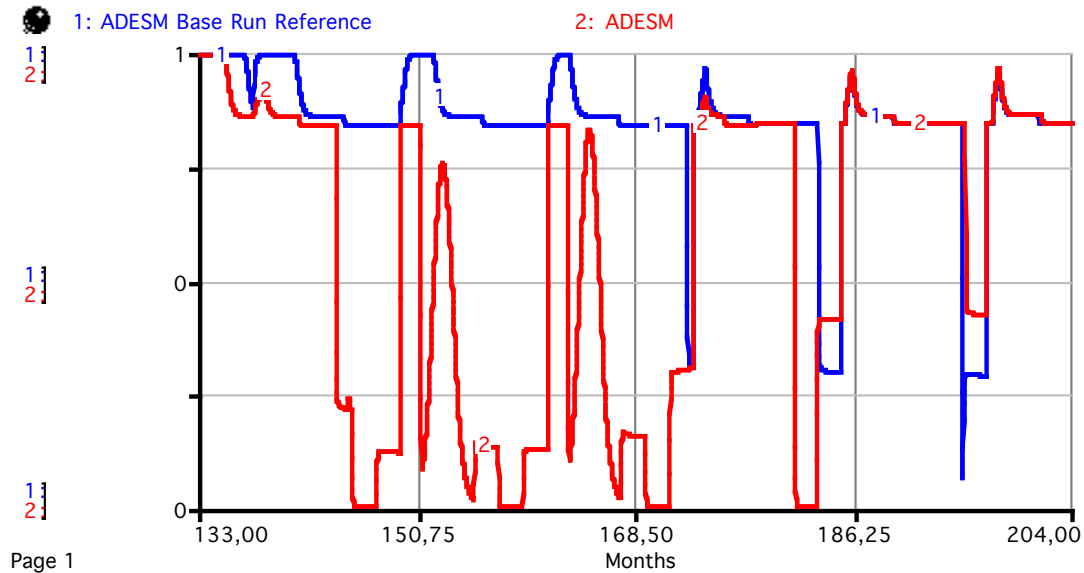
Scenario 18: Flood Loss of Cultivated Area by 20% and Zero Subsidies in 2015, followed by Subsidies Cut-in-Half to 750 Kwacha/Person/Year in 2016



Scenario 19: Flood Loss of Cultivated Area by 20% in 2015 and 2017, as well as Permanently Abandoned Fertilizer Subsidies



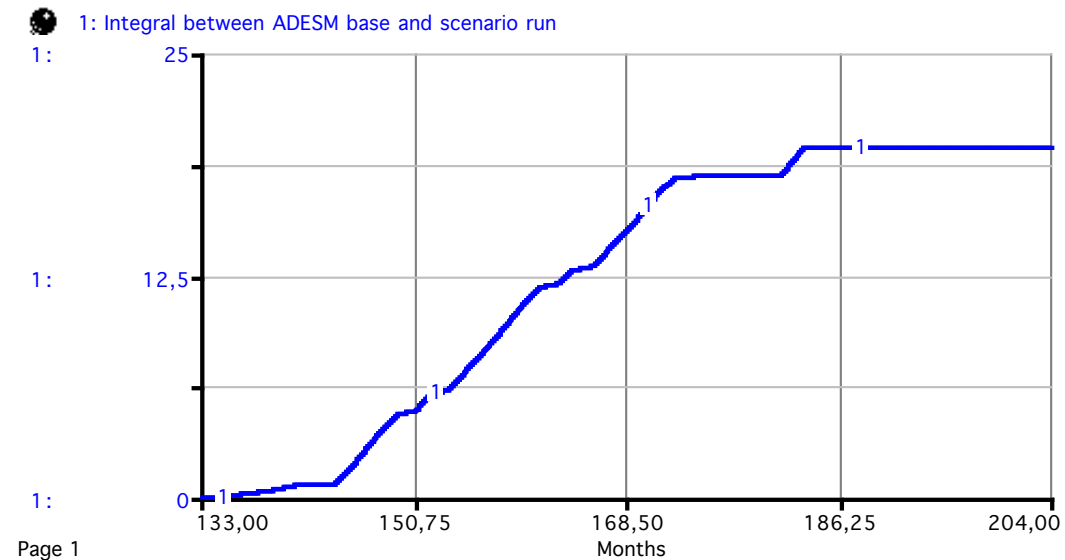
Scenario 20: Severe Droughts in 2015 and 2017 and Extreme Drought in 2016, as well as Reduced Fertilizer Subsidies in 2015 and 2018 (750 Kwacha/Person/Year) and No Fertilizer Subsidies in 2016-17



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Comparison ADESM scenario run to base run

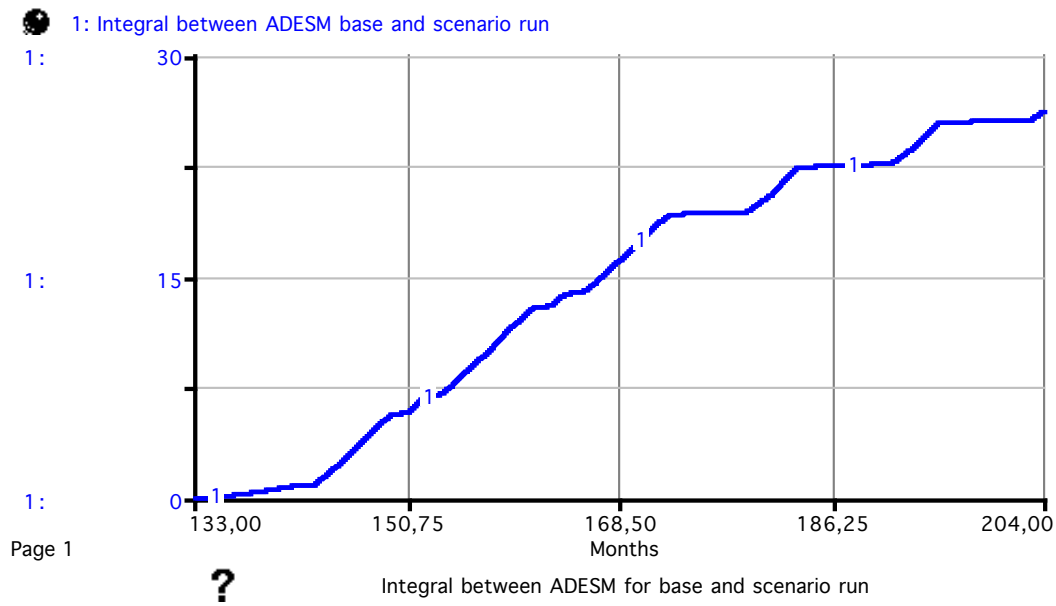
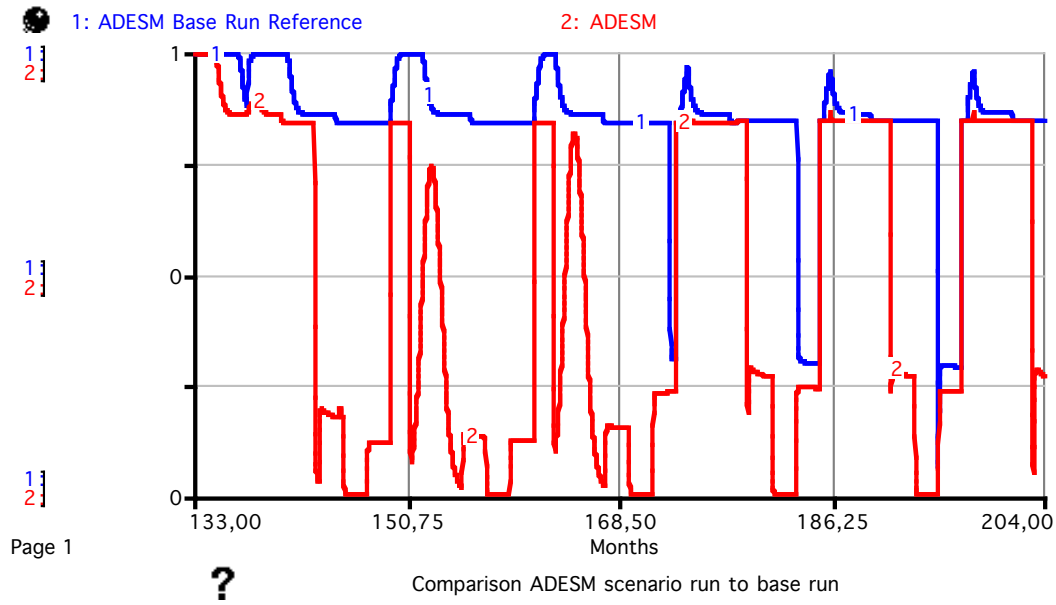


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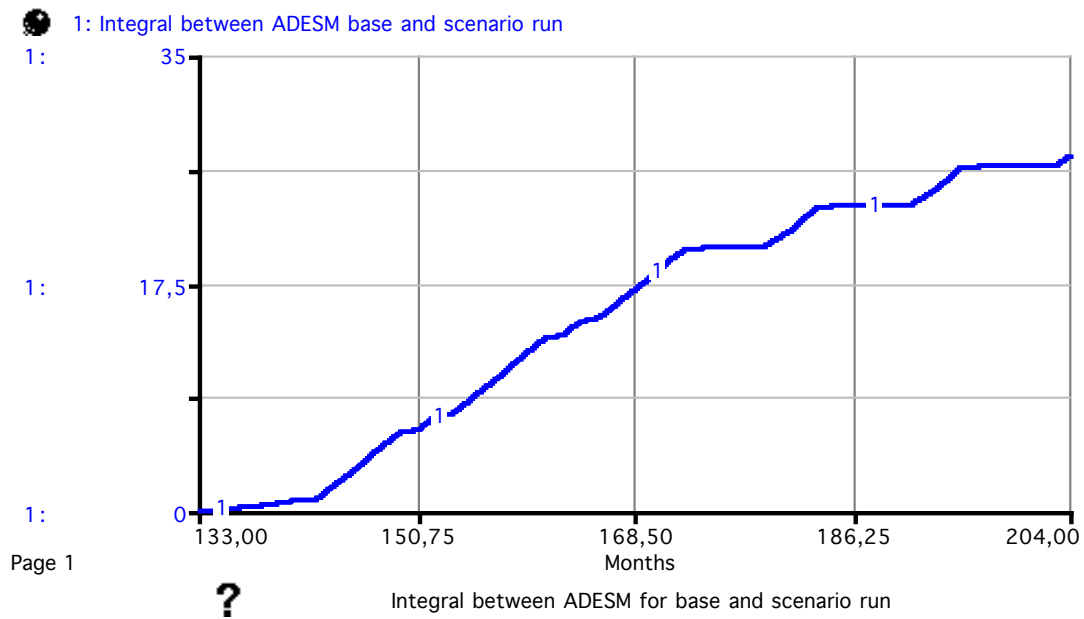
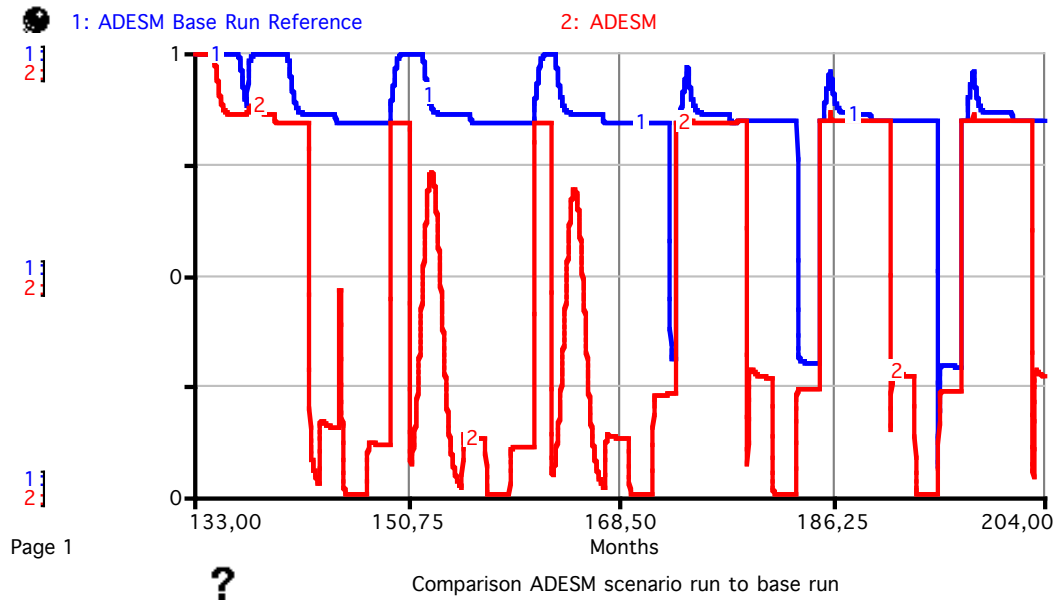
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Integral between ADESM for base and scenario run

Scenario 21: Severe Droughts in 2015 and 2017 and Extreme Drought in 2016, as well as Permanently Abandoned Fertilizer Subsidies



Scenario 22: Extreme Droughts in 3 consecutive years (2015-17), as well as Permanently Abandoned Fertilizer Subsidies



Appendix C: Data

C.1 Maize Production Data

Maize production in metric tons					
	Total maize production	Commercial farmers	Smallholder total production	Smallholder surplus	Smallholder subsistence
2004	1213599	48579	1165021	343878	821143
2005	866187	65613	800574	178803	621771
2006	1424439	84960	1339479	564348	775131
2007	1366158	97099	1269059	647863	621196
2008	1211566	85578	1125988	522033	603955
2009	1887010	229893	1657117	613356	1043761
2010	2795483	331960	2463523	1062010	1401513
2011	3020380	233484	2786896	1663043	1123853
2012	2852687	220521	2632166	1362812	1269354
2013	2532800	195793	2337008	1215244	1121764
2014	3350671	259016	3091655	1550346	1541309
2015	1821490	66219	1755271	761513	993758
2016	1823090	64551	1758539	742338	1016201
2017	1843830	64258	1779572	738971	1040601
2018	1877020	64792	1812228	745113	1067115
2019	1917240	65768	1851472	756334	1095138
2020	1961300	66966	1894334	770112	1124222

Sources for maize production data:

- All data projections from 2015-2020 are based on simulations from Gerber (2015)
- Total maize production:
 - 2004 – 2013: CSO Zambia (2015: data sheet "maize production timeline")
 - 2014: Chapoto et al. (2015)
- Total smallholder production:
 - 2004 – 2011: N. M. Mason & Myers (2011)

- 2012 – 2014: Triangulated from total maize production assuming a steady relation between commercial and smallholder production
- Smallholder surplus:
 - 2004 – 2011: N. M. Mason & Myers (2011)
 - 2012 – 2014: Triangulated from other sources as: Smallholder surplus = total maize traded (Kuteya et al., 2014) – commercial production
- Commercial farmers:
 - 2004 - 2011: Triangulated from other sources as:
Commercial production = total production – total smallholder production
 - 2012 – 2014:
Triangulated from total maize production assuming a steady relation between commercial and smallholder production
- Smallholder subsistence:
 - 2004 – 2012: Triangulated from other sources as:
SH subsistence = total smallholder production – smallholder surplus
 - 2013: Triangulated from smallholder production assuming ratio of subsistence consumption staying steady for two years.
 - 2014: Triangulated from smallholder production with information about subsistence ratio from (Chapoto, Chisanga, Kuteya, & Kabwe, 2015)

C.2 FRA Data

F.R.A. Parameter in metric tons					
	Yearly purchase	Desired reserves	Shed capacity	Silo capacity	Imports
2004	105279	0	539200	55720	9400
2005	78667	0	567020	55720	38950
2006	389510	0	566430	55270	119700
2007	396450	0	566410	55060	1458
2008	73876	0	566460	54960	1015
2009	198630	0	566480	54930	42027
2010	878570	131786	566480	54930	5704
2011	1579891	236984	590950	57370	2911
2012	1044998	156750	652990	63540	0
2013	422391	63359	737320	71920	0
2014	1031303	154695	833910	82460	0
2015	380757	76151	932780	99130	0
2016	371169	74234	1026640	125610	0
2017	369485	73897	1111110	164140	0
2018	372556	74511	1179570	212660	0
2019	378167	75633	1204760	244410	0
2020	385056	77011	1211838	248011	0

Sources for FRA Data:

- Yearly purchase:
 - 2004 – 2010: N. M. Mason & Myers (2011)
 - 2011 – 2013: Kuteya et al. (2014)
 - 2014: Chapoto et al. (2015)
 - 2015 – 2020: Assuming FRA wants to purchase 50% of smallholder surplus production
- Desired reserves:

Derived from the yearly purchase under the assumption that FRA wants to keep 20% of their yearly purchase as reserves.
- Silo capacity:

Bou Schreiber (2015)

- Shed capacity:

Bou Schreiber (2015)

- Imports:

- 2004 – 2014: FAO (2015a: Timeline under "Trade -> Crops & livestock -> Zambia")
- 2015 – 2020: Assuming no imports take place

C.3 Storage Loss Data

Residence time (months)	Accumulated storage Loss in per cent		
	Silo Loss	Shed Loss	Slab Loss
1	0,00%	0,72%	5,72%
2	0,28%	1,61%	6,61%
3	0,81%	1,83%	6,83%
4	0,82%	4,47%	9,47%
5	0,83%	6,50%	11,50%
6	1,36%	10,12%	15,12%
7	1,66%	14,97%	19,97%
8	1,86%	20,61%	25,61%
9	2,04%	26,86%	31,86%
10	2,20%	34,09%	39,09%
11	2,34%	42,22%	47,22%
12	2,46%	51,23%	56,23%
13	2,56%	61,14%	66,14%
14	2,64%	71,93%	76,93%
15	2,70%	83,62%	88,62%
16	2,74%	83,62%	88,62%
17	2,76%	83,62%	88,62%
18	2,76%	83,62%	88,62%

Sources for storage loss data:

- All data from Bou Schreiber (2015)

C.4 Roller Meal to Consumer Made Hammer Meal Price Relation Data

	Price August (ZMK/kg)				Mean
	Lusaka	Kitwe	Mansa	Kasama	
Breakfast meal (25 kg bag)	1391,0	1421,0	1505,0	1373,0	1422,50
Roller meal (25 kg bag)	915,0	975,0	1093,0	1000,0	995,75
Ratio breakfast of commercial meal	0,90	0,87	0,66	0,93	0,84
Composite commercial meal	1342,0	1362,2	1363,8	1348,4	1354,09
Consumer made meal (hammer mill)	1063	912	910	941,00	956,50
Relation roller meal to grain price					1,42

	Price February (ZMK/kg)				Mean
	Lusaka	Kitwe	Mansa	Kasama	
Breakfast meal (25 kg bag)	1536,0	1562,0	1750,0	1706,0	1638,50
Roller meal (25 kg bag)	1188,0	1261,0	1408,0	1408,0	1316,25
Ratio breakfast of commercial meal	0,92	0,88	0,62	0,96	0,84
Composite commercial meal	1506,9	1525,1	1620,1	1694,3	1586,62
Consumer made meal (hammer mill)	1185	1138	1336	1455	1278,50
Relation roller meal to grain price					1,24

Source: Nicole Mason & Jayne (2009: tables 10 & 11)

Price relation values plotted over the year assuming steady change from lean to plenty season yields this final relation:

Yearly Counter	Price relation
1	1,27
2	1,24
8	1,42
12	1,30

C.5 Urban Consumption of Meal Types Data

	Commercial meal	Hammer mill meal
Lusaka	0,899	0,101
Kitwe	0,855	0,145
Mansa	0,606	0,394
Kasama	0,317	0,683
Average	0,669	0,331

Source: Nicole Mason & Jayne (2009: tables 10-11)

Categories “consumer made maize meal via taking grain to grinding mill” and “maize meal made at grinding mill and sold by a vendor/retailer” were aggregated to “hammer mill meal” and the categories “samp” and “green maize” were excluded from the calculation to obtain the final ratio visible in the table above.

Appendix D: Interviews

In the following appendix, you will find the transcript of the two personal interviews I conducted with Dr Progress Nyanga from the University of Zambia. The interview is reported so that the core statements that he provided as answers to my questions are summarized in bullet points below the corresponding question. Information that I shared as a background for the questions and the questions that I asked are in italics, while his answers are in normal font.

D.1 Transcript of Personal Interview with Progress Nyanga on 27.04.2015

Q1: Would you agree that consumers roughly demand the same daily quantity of maize throughout the year, or are there cycles in private demand?

- The quantities consumed vary according to availability. In the lean season, where maize is scarce, consumers normally consume less maize per day.
- People would like to consume the same amount throughout the year, but they do not have sufficient access to maize in the lean season (roughly corresponding to late fall to early spring in Europe) due to shortage in availability that also lead to increasing prices, especially for maize grain.
- Grain starts to become scarce from September to December, reaching bottom at January/February.
- From March on, the green harvest starts becoming available so that the lean season gradually ends.

*Q2: In which quantities (intended to cover how much time) do customers on average buy their maize **meal**? Every day, week, or month?*

- Consumers wish to have a meal storage covering up to a maximum of four weeks' consumption. However, the actual coverage they have fluctuates with the changes in maize availability and prices over the seasons.
- Without chemical treatment, you can only store maize meal 2-3 months before it goes bad.

Q3: Do rural customers also have access to maize meal, or only to grain?

- As a general rule, rural customers have better access to grain, while roller meal is often not distributed in the villages.
- The distribution of maize grain to consumers often works in the following way: someone (most often a farmer with a maize production surplus) stores maize grain in a rural community and pays people in the hungry season in grain for their services or labour, or sells it to the community.
- In a normal year, rural communities still eat grain in the hungry period, while in the urban areas, it might run out completely. However, grain is even in times of shortage normally still cheaper than roller maize meal.
- Roller meal is usually not sold in the villages, these rural consumers often have to travel to more urbanized regions to purchase it. These travel costs makes roller meal very expensive for rural consumers, so that it is really just a measure of last resort to buy it.
- Smallholder farmers often find themselves in a bad situation in the lean season, as they need to invest in the next harvest, while having to pay more for grain.

Q4: In which intervals do grain-buying customers purchase maize grain? E.g. how much time do they want to cover with a ratio on average when buying maize? A week, month, or more?

- In the plenty season, when maize is well available, consumers wish to store grain for up to 2-3 months' consumption.
- The storage, however, changes according to availability and usually is smaller in the lean season.
- The size of the storage for an individual customer also depends on her overall purchasing power.

Q5: I assume that farmers buying grain to top up their insufficient subsistence consumption basically exhibit the same purchasing behaviour as other (rural) customers that buy grain and bring it to hammer mills themselves. Is that a suitable assumption?

- Yes, as farmers exhibit the same behaviour as the other rural poor in terms of purchasing maize.
- Many smallholder farmers do not produce sufficient maize to even cover their own subsistence consumption, so they often use up their own maize in the months after the harvest and then have to resort to buying grain in the lean period, just as other non-farmers in the rural areas do.
- Smallholder farmers usually do not plan ahead strategically with their buying behaviour, because they need to live off their grain in the plenty period as they generally do not have any other means to make cash in the plenty season. This is so because the peak demand for labour in the rural areas is in the lean season – which happens to be the period where most farming work takes place.

Q6: Apparently, the vast majority of maize (grain/meal) sales are made through traditional retail channels (large markets, street vendors), especially in rural areas. I further assume that these small retailers do not stock significant amounts of grain/meal themselves, but purchase it on a daily basis from their source. Is this a sound assumption?

- Concerning urban retailers: They usually store maize intended to cover 1-2 weeks of sales, and thus go to buy from their sources every 1-2 weeks. They then store this maize in a facility close to the market, so that they can bring a daily ration to the market every day, and quickly re-stock in case of higher-than-usual demand.
- Concerning rural retailers: There is normally no professional maize retailing in rural areas. Instead, consumers buy from other people (farmers) in the area that have larger surpluses. Rural consumers usually just find out whoever has maize in their area and go there to negotiate purchases.

Q7 – Q9: Wholesale sector

Right now, I am (based on an article about onion & fruit marketing) assuming that there is no significant wholesale market developed for maize in Zambia. This implies that retailers purchase their stocks right away from millers, farmers, and/or traders that just bring it from farm A to retailer B as soon as they purchased it. This would mean that between the miller/farmer and the retailer, there is no actor that stocks the maize and/or markets it intentionally over time, e.g. getting better prices from retailers later in the year by stocking grain he bought in June until December.

Q7: Is that a sound assumption?

Q8: Is there a significant amount of wholesalers involved in either the formal or informal maize marketing that stock maize and sell it over time?

Q9: If yes, would you say that the commercial assemblers and wholesalers could conceptually be understood as the same class of actors?

- Yes, it is true that broadly speaking, you can say that there is no developed wholesale market for maize in Zambia.
- There are middlemen/assemblers in between retailers and farmers, but they just buy from farmers and quickly sell nearly at purchase price to retailers. They thus do

not exhibit strategic behaviour or built up any meaningful reserves (stocks), but rather at as mere agents of the retailer merely fulfilling a transport service.

- One can therefore conceptually subsume retailers going to buy themselves (or farmers going to sell in bulk to the retailers) into the same class of activity as when maize is delivered by these middlemen/assemblers.

Q10-Q11: Smallholder maize sales

Q10: When and how much grain do private traders buy from smallholder farmers throughout the year; and why is the demand from these traders usually not covered by grain sales?

Q11: What are the reasons for this distribution of purchases?

- Farmers sell 70-80% of their surplus harvest in the first few months of the purchasing season, and then they become reluctant to sell more maize to retailers/assemblers as their stocks become scarce.
- As their stocks of maize become lower, smallholders want to keep their few remaining maize as a risk buffer and want to pay with maize in exchange for labour or inputs, as it is cheaper to buy labour with maize rather than cash, or exchange maize for cash later and buy agricultural inputs.

Q12-13: FRA's sales decisions

Q12: Is there a market feedback insofar that FRA reacts with their sales to information from other actors downstream in the value chain (e.g. millers, wholesalers); or are sales decisions solely governed by discretionary decisions from FRA/government officials largely disconnected from market feedback?

Q13: How does FRA determine which quantities to sell?

- The de facto main goal of FRA is to control and stabilize the roller meal price
- In general, maize is sold to big commercial millers according to these millers' demand.
- Apart from that, FRA also responds politically to price changes for maize meal, trying to stabilize prices in case of strong fluctuations.

Q14: In particular, I want to know: how does FRA determine to whom to sell?

- FRA does not sell to the informal grain retailers; they only sell to commercial millers.
- Furthermore, the government tries to help small-scale farmers by buying for above-market prices from smallholders through FRA

Q15: Does FRA always sell everything they have in stock or do they often/sometimes carry over old stocks from one (marketing) year into another?

- Sometimes, they export to not let their stocks rot away in the storages, even if they sell at a loss.
- Sometimes, they do carry over maize stocks from one year to the next

Q16: Assuming that FRA does not sell everything that is demanded (like in 2012/13, where maize meal prices spiked), what is the limiting factor for sales? Has it occurred that there are bottlenecks that stop them from selling as much as they want to?

- FRA collects maize in satellite storages (mostly slabs) around the country. This is where farmers bring their grain. The purchased maize is then moved to bigger storage facilities that are located in regional centres around the country.
 - Normally, they keep the maize in these regional storages unless there is stronger than expected demand from a particular region. Maize is then moved to that region, which can involve a lot of delays. The most likely scenario for this is that millers, who are quite concentrated in Lusaka, demand more maize than usual.
- In case of a maize shortage in a certain region, where the regional storage amount is insufficient, the maize has to be transported to the millers first (most often in Lusaka), then milled there and transported from there again until it reaches the final destination.
- It seems to mostly be a logistical problem: bad logistical planning lead to huge delays. The process of getting maize from a surplus region to the deficit region might take more than 2 months in total, involving the following steps:
 - Getting grain from satellite to central regional depots (1 month)
 - Doing the necessary bureaucratic paperwork (2 weeks)
 - The transport itself (1-2 days in region, 1 week outside)
 - Milling and then getting the meal from the miller to the region of (1 week)

Q17: When does FRA sell how much? (I read that they “mainly sell during the ‘hungry season’” from December through March)

- Zambia’s government needs money in the hungry season to finance agricultural activities (e.g. fertilizer subsidies) and they hope to get some FRA revenues in that time.
- This behaviour is also connected to the goal of stabilizing maize prices:

- During the plenty period, the millers can buy from farmers directly (who usually sell at a cheaper price than FRA and are thus preferred sources), but in the hungry period, they need to resort to FRA.
- During the hungry period, the millers have more demand from the market due to grain shortages in the informal value chain.

Q18: Is it safe to assume that purchase quantities are decided upon without responding to other actors in the market and purely at the discretion of government/FRA officials?

- Yes, that is a sound assumption.

Q19: Does FRA only buy in the purchasing season?

- The marketing season runs usually from June or July to beginning of October. The government announces the beginning and end of marketing season, FRA purchases outside of this season are not allowed.
- The purchases follow largely a bell-shaped distribution, with purchases reaching the highest volume around July/August.
- Another reason for the delay between the harvesting and FRA purchasing season is that it takes some time for farmers to process the harvest.

Q20: Is FRA's price always pan-seasonal?

- Yes, FRA has a pan-seasonal price.

Q21: I assume that all the maize is harvested in May, is that a suitable approximation?

- No, since there is a green harvest coming in from March on.
- Furthermore, the main maize harvest takes place in May and June, where both months see a similar amount of harvest. Together, the main harvest in May and June accounts for 90-95% of the total harvest.

Q22: I assume that farmers sell preferably to FRA since FRA typically offers prices above market level. Is that assumption suitable?

- That assumption is true.
- Farmers are even willing to wait for later payment by FRA because of the good prices they can get.

Q23: Is it a suitable approximation to assume that big commercial farmers store their grain for 6 months?

- In general, you can say that they wait a little bit longer to sell, as prices are higher later in the year during the lean season.
- Normally, exports are restricted by the government.
- However, if possible they prefer to export – if they can get the government to lift export bans and obtain the necessary export license. That is because they produce under quite competitive conditions due to economies of scale and can make quite good money when exporting, especially to DR Congo or Zimbabwe. Furthermore, they fear competition by the often-unpredictable FRA in the domestic market.
- However, the commercial miller's role in the domestic maize supply is not that pronounced due to their relative small combined production volume.

Q24: Is it a suitable approximation to assume that big commercial farmers sell only to large commercial millers?

- Yes, that is true.

Q25: I assume that brewers buy maize evenly distributed throughout the year and directly from millers. Are these two sound assumptions?

- Yes, they buy more or less the same amount all year round. I would estimate that they account for 5-10% of domestic demand for maize.
- However, they buy grain from farmers to mill themselves, as well as meal from millers.

Q26: I assume that livestock companies either produce their own maize for livestock feed or buy the milling by-products (such as bran or germ), so that their demand does not drain from the maize intended for sale for human consumption. Is that a suitable approximation?

- Yes, most of the big livestock companies grow their own livestock feed
- Furthermore, livestock is often feeding other crops and many just roam free and eat grass
- The impact of between livestock consumption on the maize market is therefore very weak, negligible.

Q27: What do you think are the reasons that the informal channel does not purchase sufficient quantities of maize grain to satisfy its customers throughout the year?

- A problem is often that FRA buys large amounts of maize and only sells it to the formal value chain, so that not enough is left to buy for informal traders

- Another possibility is that the surplus harvest is just too small, either because the overall harvest was small or because the farmers keep large amounts for subsistence consumption and other purposes (paying in maize, security stocks) to themselves.

Q28-29: DMMU (Disaster Mitigation and Management Unit)

Q28: What is the DMMU (Disaster Mitigation and Management Unit)?

Q29: Why does DMMU purchase large quantities of maize from FRA and what does it do with it?

- DMMU is a government agency destined to provide support to affected populations in cases of disaster or hunger. This includes the distribution of emergency food aid in maize.
- They do not stock maize themselves, but in case of an emergency they request maize from FRA and distribute it directly to consumers. It therefore does not enter the value chain in that case.

Q30: Why do farmers sell most of their maize in just a few months after the harvest?

There are a number of reasons, including:

- Storage problems: farmers often prefer to sell the grain sooner than later because storing grain at home involves a higher risk of losing maize through pests, fungi, thieves, fires etc. Note that smallholder farm storage is mostly not very advanced and prone to high losses.
- Prices for agricultural inputs like fertilizer or seeds are lower in the plenty season, so that they have an incentive to sell a lot of surplus maize early on so that they can buy all the inputs they need while prices are still low.

- Livelihood demands:
 - Many payments are timed after the typical income distribution for smallholders so that a lot of payments are due quickly after the harvest and they need cash right away. For example, school fees are due in August.
 - A queue of demands has accumulated over the lean season that now finally can and need to be satisfied as cash becomes available.
- Strategic purchasing behaviour:
 - Farmers anchor on the old FRA price, so it is risky for private traders / millers to start buying too early: if FRA has a lower price this year, they might end up having paid too much. They therefore wait until the government has announced FRA's new purchasing price, so that they have a reference point.
 - Finally, FRA and private traders often end up making most of their purchases in the weeks following the announcement of the start of the marketing season.

Q31: Who are the private buyers of maize from farmers?

- Oftentimes, they are small-scale independent maize assemblers who act as agents for millers or grain retailers.
- However, it is also common that retailers just go buying their grain directly from farmers; or especially in rural areas, that consumers go and buy their grain directly from smallholders with surplus maize harvests.
- Another possibility is that local farmers get together and make a bulk shipment of maize that they bring to the millers or FRA themselves.
 - Information is quickly distributed by the *Zambian National Farmer's Union* app on mobile phones.

- Farmers can safely can assume that the millers, competing with FRA, always want to buy maize from them because millers normally have to pay less when buying from farmers directly than when buying from FRA.

Q32: Where are the millers located?

- They are concentrated in urban centres, most notably in Lusaka, the Copperbelt, or Choma.

D.2 Transcript of Personal Interview with Progress Nyanga on 18.05.2015

Adjustment Times

Q1: AT Hammer milling: How long does it take from a grain-owning customer's decision to get his grain milled until he finally has it back home?

- It only takes a day. Normally, you just go there, give them the grain and you can take it back 2-3 hours later if there are no queues.

Q2: AT Commercial Exports: Is 1 month a suitable approximation for their export sales time (more technical, they might already have decided and planned what to do in case the lobbying for exports ban lifts works out)

- I would estimate that the paperwork takes 2 weeks and the actual logistical process of shipping and selling the maize another 2 week. So, in case that the permit is already there, one can assume that it takes the commercial farmers 2 weeks to export.

Q3: AT FRA exports: How long does it take FRA to export? Currently I am assuming 1 month (again, this concerns more the technical side, assuming that high production was foreseen and exports therefore planned for)

- 1 month seems like a reasonable assumption, as FRA always takes more time for their processes than private actors due to bureaucracy.

Q4: AT miller purchases: How long does it take a miller from the purchase decision to the actual receipt of the maize he needs? Furthermore, considering that they can source from three sources (smallholders, commercial farmers, FRA), is it okay to assume one unified adjustment time for the millers' purchases, or are the differences too great?

- For commercial and smallholder farmers, it should only take around 1 week, while for FRA it should take longer due to bureaucratic process, around 2 weeks.

Coverage Times

Q5: CT miller grain storage: For how long do millers wish to cover their production with stored grain?

- One month seems like an appropriate assumption, as it strikes a balance between the need to have a certain storage that can guard against demand fluctuations, but also considers the costs of storage.

Q6: CT customer meal storage informal: How long do customers want to store their self-milled meal? Can I assume the same time for self-milled and ready-made bought meal?

- For customers in the formal, as well as informal value chain you can assume one month's consumption as desired coverage time. This value is also stable throughout the year.

Demand structure

Q7: Grain vs. readymade meal demand: right now, I am assuming all the rural population prefers (or only has access to) grain instead of readymade meal, and 60% of the rural population. Is this plausible?

- The vast majority of urban consumers prefer the commercial meal. There is a general shift towards processed food. I would estimate that only 15-30% of urban population prefers to buy grain instead of roller meal. Furthermore, there is simply often no supply with roller meal in rural areas.
- In rural areas, more or less everyone prefers to buy grain and bring it to the hammer mill herself. Only a small class of wealthy people, mostly civil servants that often journey to the city prefer and have access to roller meal, I would estimate that they only account for 5% of the rural population.

Q8: Price grain-to-meal relation feedback: I assume that people who purchase grain have very limited budgets, so that they cannot spend more on meal, thus their effective purchase of maize falls by the ratio that meal is more expensive than grain. What do you think about this assumption?

- I think there are two trends: people try to reduce their per capita consumption when they switch to the more expensive commercial roller meal, but they also try to allocate more money to their maize budget to make up for the higher price.
- Furthermore, maize is a priority in their spending, so that they would rather cut other expenses or sell assets rather than reducing their consumption below a certain level where they would start being hungry.
- I would estimate that those consumers who have to change from grain to commercially made meal stretch the amount of maize they would normally consume in 4 weeks to 5 weeks' consumption.

Q9: Feedback from grain availability to grain demand: do you agree that people progressively lower their demand towards the minimum, as grain gets scarcer?

- Yes, I agree with that idea. However, there is a certain minimum daily consumption that people would do almost anything to not fall below.

FRA structure

Q10: Is the assumption about the cascade of maize storage suitable? (I.e. that FRA first buys maize in the slabs, then transports it to silos, fills these up until they are full and then fills up the sheds. Only when these are also full, they leave maize in the slabs)

- Yes, this assumption is plausible.

Q11: AT moving FRA maize to built facilities: how long does it take to move maize from the collection points (very basic open sheds or just slabs, I assume) to the silos or more elaborate sheds?

- Moving maize from the slabs to the permanent storage (sheds or silos) should not take more than 3 days, as FRA has contractors doing that for them so that we assume the following distribution: 1 day for getting the maize from the slab, 1 days for transporting it and 1 day for offloading it to the permanent depot.

Q12: FRA Selling season: Does FRA only sell in a certain season, or can millers buy from them throughout the year?

- Sales can happen any time throughout the year.
- When FRA gets indications from the CFS that the next harvest will be good, they start offloading their old security stocks. They get the results from the CFS around February/March.

Switches

Q13: Commercial farmers export switch: does the logic behind switch the structure make sense?

- It seems plausible. After the main harvest comes in, the government becomes willing to lift the export ban when they see that enough smallholder harvest was good enough to sustain domestic demand.

Q14: Non-FRA smallholder sales switch: does the logic behind this structure largely conform to reality?

- Non-FRA smallholder sales channels are in principal open all the time, but farmers are strategic and reserve their stocks so that they can sell to FRA later, since they

want to profit from their higher prices. The structure thus seems plausible as it represents the smallholder farmers' strategic sales behaviour.

Other Concerns

Q15: I am assuming that millers prefer to buy from commercial farmers, then smallholders (although this never really conflicts due to seasonality), and as a last resort from FRA. Is this plausible?

- This seems reasonable, as it reflects that millers usually prefer to buy from farmers because they sell faster and often at lower prices.

Q16: I am assuming that commercial farmers do not engage in any meaningful "green harvest", is that plausible?

- This assumption seems plausible.

Q17: Is milling capacity ever a problem for commercial millers? I.e. has it ever occurred that they cannot satisfy the demand of their customers? Currently, demand goes as high as ca. 100.000 mt/month in milling, and I assume they can always satisfy it. Is that plausible?

- Commercial millers have never proved to be a bottleneck in the production system. 100.000 MT per month seems to be well possible. The assumption thus appears reasonable.

Q18: Have any other bottlenecks in the maize distribution system been observed (e.g. in retailing, hammer milling, storage of any actor)? If yes, what is their nature?

- I have not observed any bottleneck in the maize marketing system that has not yet been represented in the model so far.