The Dynamics of Food Availability in sub-Saharan Africa

An Endogenous Perspective on Food Production Systems

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Abstract

Food insecurity is a major challenge of our time: In 2015, 795 million people suffered from hunger worldwide. The eradication of hunger remains a target of high-level policy programs such as the United Nations' Sustainable Development Goals. To date, research has contributed extensively to our understanding of the food security problem, its causes, and possible solutions. Within this literature, many studies used an approach based on and restricted to one discipline (e.g., soil science, plant breeding, or microeconomics). These studies have thus provided insights related to particular aspects of food security within specific disciplines. Taken together, the insights add up to a broader picture of food security related issues. However, such discipline-specific insights often failed to include important properties of food security that arise from its systemic and dynamic nature.

Food security is one of several food system outcomes that result from the dynamic interaction of various parts of food systems, such as food production activities and socio-economic and environmental drivers. Feedback mechanisms that pass through different parts of food systems, as well as their non-linear interaction and their associated accumulation processes, contribute distinctively to the dynamic complexity of food systems and shape the development of food system outcomes over time. Nevertheless, the dynamic complexity of food systems has received little attention in recent food security literature.

This dissertation enriches the food security literature by exploring the dynamic complexity of food availability in sub-Saharan Africa, the part of the world with the highest prevalence of undernourishment worldwide. There has been a long tradition of food availability policies aiming to increase food production in sub-Saharan Africa, such as fertilizer subsidy programs (FSPs), promotion of conservation agriculture, and knowledge dissemination. Despite numerous studies that evaluated these policies, little is known about how policy programs affect various parts of a food production system and how the interaction of subsystems determines the performance of the policy programs over time.

Thus, a core objective of this dissertation is to improve current understandings of the dynamic complexity of food production systems and how this leads to insufficient food availability outcomes on different levels (e.g., farm and nation). A second objective is to evaluate food availability policies with respect to the dynamic complexity of food production systems. A third objective is to enrich the food availability debate in sub-Saharan Africa on several scientific levels, specifically the theoretical, conceptual, applied, and methodological levels. The objectives are addressed in four independent articles, for which system dynamics was used as the main methodological approach. System dynamics is especially suited for studies that address and investigate the dynamic complexity of food systems because it captures feedback mechanisms, accumulation processes, and non-linearity.

The dissertation comprises a general introduction followed by four articles. The first article explores the systemic properties of food production systems in sub-Saharan Africa and their implications for the FSPs, which are among the most important food availability policies. The article develops a conceptual modeling framework for a national food production system in sub-Saharan Africa by using the causal loop diagramming method. Based on the framework, a system dynamics simulation model is formally specified and calibrated for the study case of maize production in Zambia. The analysis of the model revealed that FSPs are effective for enhancing maize availability in the short-term, but in the long-term they fail to build up stock levels of soil organic matter, which is an important systemic leverage point to increase food availability in a sustainable manner.

The second article uses an illustrative modeling approach to uncover systemic properties that lead to persistently low levels of food availability in sub-Saharan Africa and thereby seeks to explain why some policies, despite their plausible potential, fail to ensure adequate food availability. The results suggest three key concepts for understanding the performance of food production systems and related food availability policies: (1) stock management of soil organic matter, (2) policy effort threshold, and (3) land use anticipation. These concepts help explaining why sub-Saharan African countries’ food production systems and related policies persistently underperform in the provision of enough food for the respective populations.

The third article uses a system dynamics model as a point of departure to acquire data on dynamic decision-making by smallholder farmers in Zambia through a Cournot market experiment. Experiments based on Cournot markets allow the investigation of how competing participants allocate a given budget across economic activities. Such experiments typically follow standardized procedures. The article describes and discusses how the standard Cournot experiment procedures were adjusted to fit the context of rural Zambia.

The fourth paper analyzes the decision data from Cournot field experiments, in which Zambian smallholder farmers repeatedly decided how to split a given budget between a short-term oriented maize production activity (fertilizer purchases) and a long-term oriented maize production activity (soil improvement). The results revealed that the Zambian farmers had a clear and significant bias towards the short-term production activity. Nevertheless, there were distinct differences in their decision strategies, which resulted in different production outcomes that in some cases depended on the interaction with strategies that other farmers used in the same market.

Overall, the four articles in this dissertation contribute to the food availability debates in sub-Saharan Africa on a theoretical, conceptual, applied, and methodological level. The dissertation as a whole helps to conceptualize sub-Saharan African food production systems, expands theories (e.g., through the concept of anticipation of land use change), challenges common beliefs (e.g., that inorganic fertilizer is an inevitable means to increase food availability), shows that policies and decision strategies are subject to dynamic and endogenous interaction that can enhance or reduce food production, prioritizes prior knowledge based on systemic interaction (e.g., soil organic matter as an important leverage point), and expands existing methodologies (e.g., Cournot market experiments). Thus, besides the importance of discipline-specific knowledge, it advocates the complementary benefits of a system-based approach that incorporates the dynamic complexity of systems.

List of publications

Published in peer-reviewed journals:

Article 1: Gerber A. (2016). Short-term success versus long-term failure: A simulation-based approach for understanding the potential of Zambia's fertilizer subsidy program in enhancing maize availability. *Sustainability*, 8(10):1036.

Article 2: Gerber A. (Forthcoming). Why do some food availability policies fail? A simulation approach to understanding food production systems in south-east Africa. *Systems Research and Behavioral Science.*

Conference presentations:

Article 3: Lara-Arango D, Gerber A, Nyanga P and Kopainsky B. (2017). Cournot markets in the field: Dynamic decision-making in non-standard markets. Article accepted for the 35th International Conference of the System Dynamics Society, 16–20 July, 2017, Cambridge, MA, USA.

Article 4: Gerber A, Lara-Arango D, Nyanga P and Kopainsky B. (2017). How do Zambian smallholder farmers allocate their budget? Evidence of dynamic decision-making based on a Cournot field experiment. Article accepted for the 35th International Conference of the System Dynamics Society, 16–20 July, 2017, Cambridge, MA, USA.

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Contents

Articles

Introduction

1. Background

Food insecurity is one of the major challenges of our time. Although there has been a decline in the numbers of undernourished people since 1990, it has been estimated that 795 million people worldwide suffered from hunger in the years 2014–2016 (FAO *et al.*, 2015). Thus, the eradication of hunger remains an important target of high-level policy programs such as the United Nations' Sustainable Development Goals.

Policymakers responsible for food security programs can rely on a vast body of literature that describes the food security challenge and its causes (for an overview see Godfray *et al.*, 2010), offers potential solutions (e.g., Foley *et al.*, 2011), and suggests the most important research topics for the future (e.g., Pretty *et al.*, 2010). Many of the food security studies conducted to date have used a discipline-specific approach, meaning they investigated a single aspect of food security within one discipline, such as soil science, plant breeding, or microeconomics, and therefore the authors' perspectives and recommendations were restricted to the respective disciplines (Foran *et al.*, 2014). Such discipline-specific insights are crucial to the understanding of various aspects of food security, as well as for the development of effective policies. Together, discipline-specific insights add up to a broader picture of food security issues, such as provided in the review by Tilman *et al.* (2002). However, knowledge gained through the mere combination of discipline-specific insights often fails to include the important and systemic properties of food security.

Food security is one of several food system outcomes that result from the dynamic interaction between food system activities and socio-economic and environmental drivers at various levels and scales (Cash *et al.*, 2006; Ericksen, 2007). In this context, food system activities include food value chain processes (e.g., agricultural production, food processing, distribution, and consumption), which involve various actors and affect socio-economic drivers of food systems (e.g., demographics and economics) and environmental drivers of food systems (e.g., climatic conditions and resource availability). In turn, these socio-economic and environmental drivers define the basic conditions for food system actors to generate outcomes. Thus, a food system consists of subsystems that interact with each other through feedback mechanisms over time (i.e., they interact dynamically). Such dynamic feedback mechanisms, across different levels and scales, and their non-linear interaction and associated accumulation processes constitute an important source of the dynamic complexity of food systems (Kopainsky *et al.*, 2017). For example, agricultural production activities happen locally (e.g., on farms) over relatively short periods (e.g. seasons). By contrast, climate change is based on accumulation processes that occur globally and over decades (Sterman, 2008). Nevertheless, both phenomena reversely affect each other through feedback mechanisms and affect important food systems outcomes such as food security (e.g., Ericksen, 2007). However, despite the dynamic complexity of food systems and their outcomes, the dynamic interaction within food systems has received little attention in recent food security literature (Hammond and Dubé, 2012).

This dissertation contributes to and enriches the rather thin body of systemic food security literature (i.e., literature that investigates the dynamic and endogenous interactions within food systems). The dissertation's focus is on the part of the world with the highest prevalence of undernourishment: sub-Saharan Africa. In sub-Saharan Africa, approximately 23% of the population — 220 million people — suffered from hunger in the years 2014–2016 (FAO *et al.*, 2015). Although none of the food security pillars—food availability, affordability, utilization[1], and stability[2]—reach sufficient levels in sub-Saharan Africa and thus constitute causes of hunger (GFSI, Undated), this dissertation focuses specifically on food availability. Food availability is an important outcome of the supply side of food systems. In many sub-Saharan African countries, chronically low levels of food availability have triggered the implementation of policy interventions with the objective to increase food availability. Such policy programs have included fertilizer subsidy programs (FSPs), the promotion of conservation agriculture, and knowledge dissemination (e.g., Ministry of Agriculture and Food Security, 2011). A vast body of literature has been generated in connection with the programs and separate analyses and evaluations have been made of the respective programs (see, for example, Druilhe and Barreiro-Hurlé, 2012, for an overview of fertilizer subsidy programs). However, little is known about how the policy programs have affected various parts of food production systems, such as the socio-economic, biological, and environmental subsystems, and how these subsystems feed back to the performance of the policy programs over time. In other words, the endogenous and dynamic interaction between policies and food production systems is barely understood (Hammond and Dubé, 2012).

2. Objectives and research questions

Food production systems in sub-Saharan Africa persistently underperform in providing enough food to their respective populations. One core objective of this dissertation is to improve the understanding of the dynamic complexity of food production systems and how it leads to insufficient food availability outcomes on various levels (e.g., farm, nation, growing season, decades). The second objective is therefore to evaluate food availability policies in view of the dynamic complexity of food production systems by taking into account the aforementioned levels. The third objective is to enrich the food availability debate relating to sub-Saharan Africa on

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[1] Utilization includes the processes leading to nutrient uptake to the human body.

[2] i.e., stability over time.

several scientific levels, specifically the theoretical, conceptual, applied, and methodological levels. These objectives are addressed by answering the following research questions.

The first set of research questions focuses on understanding the dynamic complexity of sub-Saharan African food production systems and how the resulting food availability outcome may be improved:

1. What are the food production system processes on a national level that endogenously determine the dynamics of food availability in sub-Saharan Africa?
2. What structural (endogenous) properties of sub-Saharan African countries' food production systems explain the persistently insufficient levels of kilocalories available to feed a country's population?
3. What are the leverage points in a sub-Saharan African country's food production system that may be employed to enhance food availability in a sustainable manner?
4. What are strategic areas of policy interventions that may be utilized to reach adequate and sustainable levels of food availability in sub-Saharan African food production systems?

The answers to these questions will contribute to the understanding of sub-Saharan African food production systems with regard to food availability and highlight policy interventions on an aggregated (national) level. However, the implementation and thus the success or failure of production-oriented food availability policies happens on the farm level, where farmers decide whether to apply certain production activities. Hence, a second set of research questions focuses on farmers' dynamic decision-making:

5. What methodological approach allows the investigation of dynamic farm management decision-making in rural areas of sub-Saharan Africa?

6. How do sub-Saharan African smallholder farmers dynamically allocate a given budget across short-term and long-term oriented production activities, such as fertilizer purchases and soil improvement?
7. How do the allocation decisions between short-term and long-term oriented production activities shape the performance of food production systems in terms of food availability?

Together, the seven research questions are intended to bring a multilevel perspective to the dynamic complexity of food production systems and food availability in sub-Saharan Africa. The research questions are addressed in four articles, each of which is presented in a separate chapter in this dissertation.

3. Study case: Zambia

Zambia is used as an exemplary study case in most of the articles because its food availability situation and food production system are similar to those in many sub-Saharan African countries. Zambia is a landlocked country in southern Africa, with a rapidly growing population, currently 17 million people (FAO, undated, a). After the export-oriented mining sector, agriculture is the second largest contributor to the country's gross domestic product and mainly produces food to cover the nation's own food needs. Maize is the staple food for most Zambians and has accounted for 55% of the population's total calorific intake since the mid-1980s (FAO, undated, b). It is preferably eaten as "Nshima," a mash made from maize flour, which if possible is flavored with sauces.

Zambia's food production system consists predominantly of smallholder farmers who consume large shares of their harvests and only sell parts to generate cash (Tembo and Sitko, 2013). Most agricultural goods are produced within a low-input and rain-fed farming system that is poor in capital endowment. The rainy season usually lasts from November to March, which means that farmers can generate one harvest per year. Depleted soils and low fertilizer application rates lead to chronically low yields and harvests and thus to insufficient levels of food availability. Furthermore, food availability is subject to seasonal and annual variations and in years of ‘bumper harvests’, the country may even produce enough food to cover the needs of its population.

The Government of the Republic of Zambia (GRZ) has a long tradition of implementing policies to increase food production and to improve the unsatisfactory food availability situation (Wood *et al.*, 1990). Important policies for food availability include FSPs, conservation agriculture (CA), and agricultural extension, which have been implemented and supported with considerable financial means. However, previous research relating to the policies has revealed mixed results in terms of food availability improvement (e.g. for FSPs, see Druilhe and Barreiro-Hurlé, 2012; for CA, see Giller *et al.*, 2009).

The situation in Zambia is representative of many sub-Saharan African countries in terms of population development, the food availability situation, the staple crop, farming system characteristics, and policy instruments. Thus, the findings from this dissertation may be applicable to other sub-Saharan African countries with similar properties, especially because they build on a general, illustrative modeling approach, which is described in the following section.

4. Choice of methodological approaches

The main methodological approach that I used to answer the research questions is system dynamics. System dynamics allows studying the relationship that exists between structure and behavior in complex and dynamic systems, so as to understand the structural origin of a problematic dynamic development and to identify policies for the purpose of modifying that development (Forrester, 1968; Sterman 2000). System dynamics is especially suitable to complement discipline-specific research in food production systems because it enables a rich representation of feedback processes that cut across various subsystems of food production systems (Hammond and Dubé, 2012). While other dynamic modeling approaches such as agent-based modeling analyze the interaction of a system’s individual actors (i.e., agents) on a micro level (Schieritz and Milling, 2003), the system dynamics approach focuses on the interplay of subsystems over time on an aggregated macro level (Richardson, 1991). By integrating domain-specific knowledge into a system and analyzing the interaction of the different subsystems through simulation, the system dynamics approach is not only a way to structure knowledge, but also to prioritize prior findings, to reveal systemic insights such as leverage points and to detect knowledge gaps. System dynamics is a suitable approach for analyzing systems with several, often conflicting, outcome targets and for policy assessment by means of simulation.

I use an illustrative modeling approach (Morecroft, 2015) in my research for this dissertation. The approach focuses on realistically representing the core feedback processes of a system, instead of a detail-rich representation of individual subsystems (as in analogue models). Illustrative models allow conclusions to be drawn on a conceptual level, but they are inappropriate for the provision of detailed practical advice, such as advice on the implementation of a specific policy. I considered an illustrative system dynamics modeling approach suitable and directly applicable to answer the first set of research questions. The answers to the second set of questions were mainly based on a Cournot market experimental approach that included an illustrative system dynamics simulation model.

5. Overview of Articles 1–4

This thesis is based on four articles reviewed in this section:

Article 1: Gerber A. (2016). Short-term success versus long-term failure: A simulation-based approach for understanding the potential of Zambia's fertilizer subsidy program in enhancing maize availability. *Sustainability*, 8(10):1036.

Article 2: Gerber A. (Forthcoming). Why do some food availability policies fail? A simulation approach to understanding food production systems in south-east Africa. *Systems Research and Behavioral Science.*

Article 3: Lara-Arango D, Gerber A, Nyanga P and Kopainsky B. (2017). Cournot markets in the field: Dynamic decision-making in non-standard markets. Article accepted for the 35th International Conference of the System Dynamics Society, 16–20 July, 2017, Cambridge, MA, USA.

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Article 1: Short-term success versus long-term failure: A simulation-based approach for understanding the potential of Zambia's fertilizer subsidy program in enhancing maize availability

Article 1 reports a case study of the Zambian food production systems and investigates the systemic properties of FSPs, which are among the most important food availability policies in sub-Saharan Africa. Many economic aspects of FSPs have received attention in previous research. However, the interaction between FSPs and the biological elements of the food production systems has largely been overlooked in the literature to date. To fill this gap, a system dynamics model was developed and applied to examine the FSPs' short-term and long-term potential for increasing maize availability in Zambia. The results revealed that FSPs are a viable means to enhance target variables in the short-term (such as maize availability). However, farm practices that build up stock levels of soil organic matter (SOM) are a better and more sustainable long-term strategy to increase maize availability because they trigger a systemic leverage point. While the role of SOM in the FSP debate has largely been overlooked, Article 1 makes the links between FSPs and SOM explicit. Additionally, it relativizes some common beliefs (e.g., that the use of inorganic fertilizers is inevitable to increase food production sustainably) and suggests a gradual shift towards alternative food policy strategies that are more sustainable than FSPs.

Studying one of the most applied food availability policies based on a specific case meant that not only could FSPs be evaluated from an endogenous point of view, but also increased the general understanding of the Zambian food production system. The system dynamics model used in the study as reported in Article 1 was developed by integrating relevant theories into a framework with the relevant processes that determine food availability on a national level. This conceptualization of sub-Saharan African food production systems and the formalized model served as a stepping stone for the subsequent three articles.

Article 2: Why do some food availability policies fail? A simulation approach to understanding food production systems in south-east Africa

Article 2 is a theory building article that aims at awakening interest and increasing understanding about system dynamics outside the system dynamics community. The article explores fundamental mechanisms of food production systems in sub-Saharan Africa that lead to persistently insufficient levels of food availability and it addresses the problem of potentially beneficial policies that fail to provide enough food calories. The systemic mechanisms and policy interaction are analyzed through an illustrative model that constitutes a condensed generalization of the food production system model in Article 1 (Gerber, 2016).

The results suggest three key concepts for understanding the performance of food production systems: (1) stock management of soil organic matter, (2) policy effort threshold (this concept suggests that a threshold for policy endowment exists, e.g. in financial terms, above which the policy helps to produce enough food), and (3) land use anticipation (this concepts suggest actively anticipating land use change instead of reacting to increasing food demands). These concepts help explaining how dynamic interactions can cause potentially beneficial policies to fail to provide enough food calories and they offer leverage points for policy formulation.

Article 3: Cournot markets in the field: Dynamic decision-making in non-standard markets

The research for Article 3 extended the common Cournot market experimental approach to the field setting of rural Zambia in order to gain information about the dynamics of Zambian smallholder farmers' decision-making. Commonly, Cournot market experiments are conducted to contribute findings to theoretical debates in economics by using dynamic models as a base for interaction between the experiments' participants. The study reported in Article 3 used the dynamic and interactive setting of Cournot experiments and adapted it in order to gain insights into dynamic decision-making. This provided a methodological extension to standard Cournot market experiments. The article describes the adjustments to the standard protocol of Huck *et al.* (2004) that were needed to fit the field setting of rural Zambia, and my co-authors and I discuss the strengths and limitation of those adjustments.

The participating farmers were engaged in the experiments and, according to their feedback, they had various learning outcomes that they normally would not otherwise have had from existing capacity building practices. Thus, besides the usefulness of the proposed approach for gaining experimental data about dynamic decision-making, the study revealed that the approach also has potential for building adaptive capacity (e.g., in agricultural extension, which is the process of transferring scientific knowledge about farming practices to farmers).

Article 4: How do Zambian smallholder farmers allocate their budget? Evidence of dynamic decision-making based on a Cournot field experiment

Article 4 investigates dynamic decision-making of Zambian smallholder farmers and the implications in terms of maize production. The approach developed for the study reported in Article 3 was applied in field experiments, in which decision-makers (i.e. farmers) participated as players in the experiment. Little is known about how sub-Saharan African smallholder farmers make allocation decisions in a dynamic context (Saldarriaga *et al.*, 2014). Thus, the farmers repeatedly decided on how to allocate a given budget to a short-term oriented maize production activity (fertilizer purchases) and a long-term oriented maize production activity (soil improvement), based on dynamic farm and market information. Overall, the results revealed that Zambian farmers had a clear and significant bias towards the short-term production activities. Nevertheless, they followed distinct decision strategies with performance implications; i.e. the farmers applied distinct decision heuristics that led to significant differences in maize production. While the majority of farmers applied decision strategies that did not take into account the provided farm and market information when making their decisions, the minority of farmers adjusted their decisions dynamically, based on the provided information. Simulation experiments with the decision strategies revealed that most strategies resulted in rather stable production patterns when a market comprised farms with varying decision strategies. However, the production pattern of some decision strategies strongly varied when the strategy interacted with other strategies in the same market and their production therefore was sensitive to the market's endogenous interaction.

According to the classification provided by Kim and Cameron (2013), Article 4 covers a wide spectrum of characteristics in decision-making studies, such as finding analytical factors that explain decisions, normatively evaluating the outcome of decisions, and providing prescriptive aid to inform policy design. The results indicate that in some cases it is crucial to analyze decisions not only in isolation, but also in an endogenous and dynamic context.

6. Conclusions

Overall, the four articles in this dissertation contribute to the debates on food availability in sub-Saharan Africa on a theoretical, conceptual, applied, and methodological level. Furthermore, the endogenous point of view taken in this dissertation contributes the following eight key findings to the literature.

First, the conceptualizing of a theory-based framework and specifying it into a formal model (see Article 1) offers a viable means to connect a variety of elements of the food production system in sub-Saharan Africa. Article 1 identifies several core feedback processes of these food production systems that determine food availability and how food availability develops over time. The processes include three short-term feedback mechanisms that balance food demand and supply, and three long-term feedback mechanisms, one of which drives agricultural land development and two mechanisms accumulate soil organic matter. The visual representation of these processes in the form of causal loop diagrams (Forrester, 1968; Sterman, 2000) makes food production system processes explicit and thereby more easily accessible for further research. Thus, future studies may build on the causal framework of this dissertation by challenging it, expanding upon it, and adding details to it.

Second, Article 2 provides theoretical explanations for the persistently insufficient levels of food availability from a dynamic and endogenous perspective. The explanations include lagging land use change compared with the development of food demand, the endogenous interplay of policies that can reduce benefits of each policy, the policy intensity threshold, and the weak capacity to adjust food supply to demand due to failures in input markets (e.g., the fertilizer market). Although not all of these explanations are new from a discipline-specific perspective, they are assessed in this dissertation on the basis of a systemic evaluation that takes into account the dynamic complexity of food production systems. Additionally, the systemic perspective allows for insights into the endogenous interplay of subsystems—insights that would most likely not be detected in a discipline-specific study (e.g., the positive and negative synergies of combining policies or the lagging land use adjustment).

Third, the articles reveal that soil fertility (SOM in particular) is an important long-term leverage point in sub-Saharan African food production systems, because it helps to increase food production and strengthens the systems' sustainability and resilience to external shocks. While this finding is not new in general, it is emphasized from a systemic perspective in this dissertation. Article 1 shows that SOM is manageable through direct and indirect interventions, and thus constitutes a potential point of policy interventions.

Fourth, the above-mentioned findings result from illustrative models that represent feedback processes on a high level of aggregation. This implies that the findings are neither predictive, nor suitable for inclusion in advice given on the detailed and practical implementation of policies. Instead, the endogenous mechanisms and leverage points constitute ideal types of strategic policy intervention areas and need further specification for implementation. Generally, the findings of this dissertation suggest that there is not one easy solution to increase food availability in sub-Saharan Africa. Instead, a mix of short-term and long-term policy instruments is needed to achieve adequate levels of food availability at a sustainable level. Moreover, when designing combined policy interventions, it is crucial to consider the timing and sequencing of the interventions to bridge food availability gaps, and it is important to consider the endogenous interaction of the interventions. For example, building up SOM stock levels is a strategic area of policy intervention, but it also involves time-consuming accumulation processes that only pay off after years of persistent policy application. By contrast, inorganic fertilizer application, which is the target of important policy programs such as FSP, immediately increases food production. However, it does not trigger a systemic leverage point in the long-term and its effects soon show signs of weakening. For practical purposes, this implies that a gradual and continuous shift from inorganic fertilizer application towards soil improvement policies is needed, and that long-term planning should be a central element in designing policies.

Fifth, the proposed extension of the Cournot market experiment approach to match the field setting of rural Zambia was a suitable means to gather data about dynamic farm management decision-making and triggered a high level of engagement by the participants. Additionally, the famers' reactions indicated that the approach not only has the potential to generate data, but also might be a lively and welcome addition to current capacity building activities.

Sixth, when allocated a budget for fertilizer purchase and soil improvement, Zambian smallholder farmers showed a clear and significant bias towards fertilizer purchases. This finding is in line with previous hypotheses that smallholder farmers operate with high discount rates for benefits that will be felt far in the future (Donovan and Casey, 1998). Additionally, the bias towards short-term oriented production activities may explain why it is difficult to scale up long-term oriented production activities such as conservation agriculture (Giller *et al.*, 2009).

Seventh, despite Zambian smallholder farmers' preference for short-term production activities over long-term ones, the studied farmers applied a wide range of distinct decision strategies with performance implications in terms of production. This dissertation presents evidence that the majority of farmers did not base their decisions on dynamic farm and market information, but instead applied heuristics with a static and an a priori defined foundation. The performance of those decision strategies depended on how close they were to a calculated, optimal decision pattern and they were not sensitive to the endogenous interaction with other market players. However, some farmers made dynamic decisions in response to their changing farm and market context. While such dynamic decision strategies offer farmers the potential to adapt flexibly to a changing environment, the performance of such decision strategies is especially prone to dependence on the behavior of other actors in the market and are therefore highly context-specific. In terms of agricultural extension, the diverse strategies mean that a shift is required from a policy instrument focused view to an adaptive capacity focused view. Initially, this suggestion may seem to conflict with the strategic areas of policy interventions discussed above (e.g., increasing SOM levels or anticipating land use change) because they may reflect a policy instruments' view. However, the contradiction can be resolved by taking into account different levels. On a national level, the strategic areas of policy interventions constitute strategic guidelines for policy formulation that are based on a systemic prioritization. By contrast, on a farm level, not all strategic areas of policy interventions may constitute suitable policy options. Thus, a dynamic environment accentuates the importance of agricultural extension for developing the adaptive capacity of farmers so that they are able to adapt and choose the right solutions (from a set of potential policy options), which will suit the changing environment of their farms best.

Eighth and finally, the endogenous perspective in this dissertation provides insights into food availability debates that would normally not be gained with discipline-specific approaches. Discipline-specific insights are invaluable for understanding food production systems and taken together they add up to a broader picture of food security issues. However, in this dissertation I have demonstrated the complementary benefits of a system-based approach that incorporates the dynamic complexity of food production systems.

7. Literature

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Article 1

Short-Term Success versus Long-Term Failure: A Simulation-Based Approach for Understanding the Potential of Zambia's Fertilizer Subsidy Program in Enhancing Maize Availability

Short-Term Success versus Long-Term Failure: A Simulation-Based Approach for Understanding the Potential of Zambia’s Fertilizer Subsidy Program in Enhancing Maize Availability

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Abstract

In Sub-Saharan Africa, food-related policies such as fertilizer subsidy programs (FSPs) have undergone a revival and triggered a controversy about their impact. In this article I applied a simulation-based approach to examine the FSPs’ short- and long-term potential for increasing maize availability in Zambia. The study revealed that FSPs are an effective policy measure to enhance maize availability in the short-term. However, in the long-term, the food system becomes dependent on the government’s annual expenses. The dependency occurs because FSPs fail to build up adequate stock levels of soil organic matter (SOM), which is an important source of resilience and productivity, and thus represents a long-term leverage point in Zambia’s maize production system. For this reason, alternative policies that combine increasing productivity and building up SOM stock levels were analyzed. They were found to be a viable means for enhancing long-term maize availability. The study concludes that gradually reducing investments in FSPs while simultaneously promoting farming practices that build up SOM stock levels is a promising strategy to enhance maize availability sustainably.

Keywords: Zambia; maize; food production system; fertilizer subsidy program; soil organic matter; food availability; policy analysis; simulation

1. Introduction

In Sub-Saharan Africa (SSA) food-related policies have undergone a revival due to rising concerns about food security and lagging economic development. In this context many countries have re-introduced fertilizer subsidy programs (FSPs) since the mid-1990s. Examples include Malawi (re-introduced fertilizer subsidies in 1998), Nigeria (in 1999), Zambia (in 2000), Tanzania (in 2003), Kenya (in 2006) and Ghana (in 2008) [1]. FSP goals are manifold and include increasing fertilizer use, improving soil fertility, improving food security, alleviating poverty, and fostering economic growth.

The impacts of the re-introduction of FSPs have been analyzed with a focus on economic aspects [2]. Although FSPs contribute to increasing fertilizer use, which translates into higher food production, they have numerous shortcomings [3]. The most commonly recognized pitfalls include low yield response to fertilizer application, crowding out of private fertilizer sale activities, poor targeting towards farm households in need, low cost effectiveness, inflexibility to adjust fertilizer composition to regional conditions and implementation problems such as late fertilizer deliveries [4–6]. Despite this, governments in SSA spend considerable amounts of their state budgets on FSPs. In 2011, ten countries in the region spent approximately USD 1 billion on input subsidy programs, which accounted for almost one-third of their public agricultural expenditure [2]. Zambia is an exemplary case where FSPs have been increasingly applied and remain popular [7]. Given the broad goals and the high costs of FSPs, the success of the expenditure is crucial not just for governments but primarily for the food security status of the population.

To develop agricultural sectors in SSA, there exists wide agreement that higher use rates of inorganic fertilizers are necessary to increase agricultural productivity and food production (e.g., [3,8]). However, the question of how to achieve the higher fertilizer use rates has been controversially debated. Some have stressed the importance of FSPs and aim to overcome implementation challenges (e.g., [9]), while others have recommended downsizing expenditures on FSPs and allocating the savings to other well-known growth promoters such as infrastructure development [4,10]. Thus, the FSP debate is polarized.

A blind spot in the debate is that “the critical relationship between soil conditions and fertilizer response has been largely overlooked to date in the economics literature on fertilizer promotion policy” [2]. In SSA, soil fertility depletion causes soils to lose the ability to provide food [11]. Within soils, soil organic matter (SOM) is a crucial component for plant production because it influences the soil’s physical, chemical and biological properties [12] and, in turn, low SOM levels lead to low agricultural productivity and low fertilizer efficiency in SSA countries, such as Zambia [13]. Despite these facts, only few articles to date mention the importance of SOM in the FSP debate (e.g., [3,14,15]). These articles point out that fertilizer application helps to increase SOM levels but without closely investigating or specifying the interactions between FSPs, productivity, SOM, and food production. However, the understanding of these interactions is vital for designing sustainable, long-term oriented policy interventions. Consequentially, policymakers face a knowledge gap that requires broad approaches, including tools that go beyond statistical analyses and that take into account dynamic effects [15].

Accordingly, I used a simulation-based approach appropriate to analyze the complex long-term interactions between FSPs, SOM, maize production, and maize availability in this study [16]. In contrast to previous approaches, I do not report new data, demonstrate the existence of a new variable, or specify the strength of a link between existing variables. Instead, the main contribution of my work is to provide new insights from links and theories that are already well established in the literature. More specifically, my contribution to the FSP debate arises from two activities. First, I conducted an in-depth theory and literature review to integrate relevant concepts into a food production system framework using causal loop diagramming [17]. Second, I developed and analyzed a mathematical bio-economic simulation model for the specific case of Zambia, from which I derived new knowledge-based insights.

This article extends the FSP debate in several ways. First, it provides a feedback-based framework of food production systems. The visual integration of theories and variables into one framework makes the structural properties of the interaction between FSPs, SOM, maize production, and maize availability explicit. Second, the quantitative simulation model allows for analyses of the complex interplay of the system's structure and its trajectory over time. The study finds that FSPs are a viable means to enhance many target variables in the short-term, such as fertilizer use, maize yield, maize production, and maize availability. However, in the long term, FSPs fail to increase SOM levels adequately, which represent a systemic leverage point and important source of resilience. Thus, the long-term success of FSPs depends on sustained government expenditures. Promoting farming practices that build up SOM stock levels are a promising alternative to FSPs for sustainably enhancing maize availability. Third, the study demonstrates the usefulness of a feedback-based simulation approach for policy evaluation and provides a stepping-stone for further FSP research focusing on broader perspectives.

The article is organized as follows. First, I introduce to the method and the study case, Zambia. Thereafter, I develop the modeling framework, specify it into a mathematical simulation model, and then validate, calibrate, and analyze the model. Finally, the article ends with discussion and conclusions.

2. Method and Study Case

2.1 Simulation Approach

A simulation model was developed to investigate the dynamic interaction between FSPs, SOM, maize production, and maize availability in Zambia. The simulation-based approach focuses on a high level of aggregation and allows the identification of leverage points, strategic areas of action and fundamental mechanisms of a complex system. However, the systemic integration on an aggregated level comes at the cost of some abstraction and thus the inability to represent phenomena on a detailed level. The dynamic complexity of a system arises though the non-linear interaction of feedback loops and the accumulation processes involved. To capture this dynamic complexity, a two-step approach was applied.

As a first step, an in-depth literature review was conducted to develop a modeling framework applying the causal loop diagramming method [17] to represent the system's structure and feedback mechanisms. With this method, structural assumptions about causal relations are made explicit by visually linking cause-and-effect variables through arrows directed towards the effect. Positive and negative signs at the arrowhead show the polarity of the causality. A plus sign (+) indicates that a change in the cause variable leads to an equally directed change in the effect variable. A minus symbol (–) indicates that a change in the cause variable leads to a reverse-directed change in the effect variable. Feedback mechanisms, which are also referred to as feedback loops, consist of such cause-and-effect relationships, which build a circular chain of causation. Feedback loops show either a reinforcing or balancing mode of behavior. The former self-reinforces whichever behavior is present, and the latter adjusts the current behavior towards a goal. A framework based on causal loop diagramming is a qualitative statement about a system's structure, and in my study, the framework served as a base for developing the quantitative simulation model.

In a second step, the modeling framework was specified into a formal, mathematical simulation model. Technically, the model consisted of non-linear difference equations that were numerically integrated. The model presented in this article was calibrated for the specific case of Zambia using time series and validation procedures, following Barlas [18]. Once the model was robust, it served as a "virtual playground" in which to test different policy experiments. The applied two-step approach is useful for evaluating sustainability programs [19] due to its long-term perspective that captures feedback dynamics [16].

2.2 Zambia’s Fertilizer Subsidy Program

As in other SSA countries, maize is the staple crop of Zambia’s rapidly growing population. Since the mid-1980s, it has accounted for 55% of the population’s total calorific intake on average [20]. Most of the maize consumed in Zambia is produced domestically by resource-poor smallholder farmers working within a low-input and rain-fed farming system. The soil fertility levels are low, resulting in low yield returns relative to fertilizer use [21]. Accordingly, food availability remains chronically below the required level.

To increase maize availability, Zambia has a long tradition of FSPs in its maize sector. Agricultural policies in the period from independence in 1964 to 1990 were characterized by a nationwide network of input supply and collection centers operating under a parastatal organization [22]. After an intermediate period of economic liberalization during the early 1990s, with little state involvement in the agricultural sector, the government of Zambia reintroduced a fertilizer credit program in 1997 that turned into a large-scale input-subsidies program in 2002 [4]. Since the re-introduction of the subsidized fertilizers in 1997, there has been an increasing trend in consumption from ca. 20,000 tons in 1997 to ca. 200,000 tons in 2014 [7].

Despite the increasing popularity of Zambia’s FSPs, little research exists to help policymakers understand the short-term and long-term impacts of the program on SOM and the interactions between the program, SOM, maize production, and maize availability. As already mentioned, such an understanding is crucial for the design of policy instruments with sustained benefits.

3. Modeling Framework

In this section I describe a framework based on an in-depth literature review of relevant fields that include production theory (e.g., [23]), soil dynamics (e.g., [24]), plant nutrition (e.g., [25]), farmers’ allocation decisions (e.g., [26,27]), and commodity markets (e.g., [28]). In this theory integration I focus on plant production, since animal-based food products play a subordinate role in Zambian diet.

3.1 Fertilizer, Yield, and Soil Dynamics

A core part of the framework represents the interaction between fertilizer, yields, and soil dynamics. I summarize the vast literature of these fields by representing the long-term dynamics on a country level. The first set of relations is captured in the lower part of Figure 1, which shows *total fertilizer application* as negatively influenced by *fertilizer prices* and positively influenced by *private fertilizer expenditure* and *public expenditure on fertilizer subsidies*. The negative arrow polarity expresses that *total fertilizer application* decreases with increasing *fertilizer prices*. Similarly, the positive arrow polarity expresses that *total fertilizer application* increases (decreases) with increasing (decreasing) *public expenditure on fertilizer subsidy* and *private fertilizer expenditure*. The links between total expenditure, price, and quantity of fertilizer are well founded in microeconomic theory (e.g., [26]).

SOM is conceptually split into two elementary components—carbon and nutrients—according to their different roles in the growth process. Figure 1 shows that *total fertilizer application*, *soil organic carbon*, and *soil organic nutrients* positively influence *yield* through the intermediate variable *nutrient uptake*. Whereas the links between *soil organic nutrients*, *total fertilizer applications*, and *yields* have a strong theoretical and empirical foundation (e.g., [8,21,25]), the links between *soil organic carbon*, *nutrient uptake* and *yields* exist, yet many mechanisms with respect to SOM still need to be researched [29].

The remaining links on the left side of Figure 1 represent SOM dynamics and reflect the assumption that plant residues partly remain on the field as by-products of the harvested yields. These plant residues increase two SOM stocks: *soil organic nutrients* and *soil organic carbon*. This assumption is well founded, both theoretically and empirically (e.g., [24]). While above-ground plant residues are burned or partly removed from the field and serve purposes such as feeding animals and building construction, below-ground biomass stays entirely within the field boundaries.

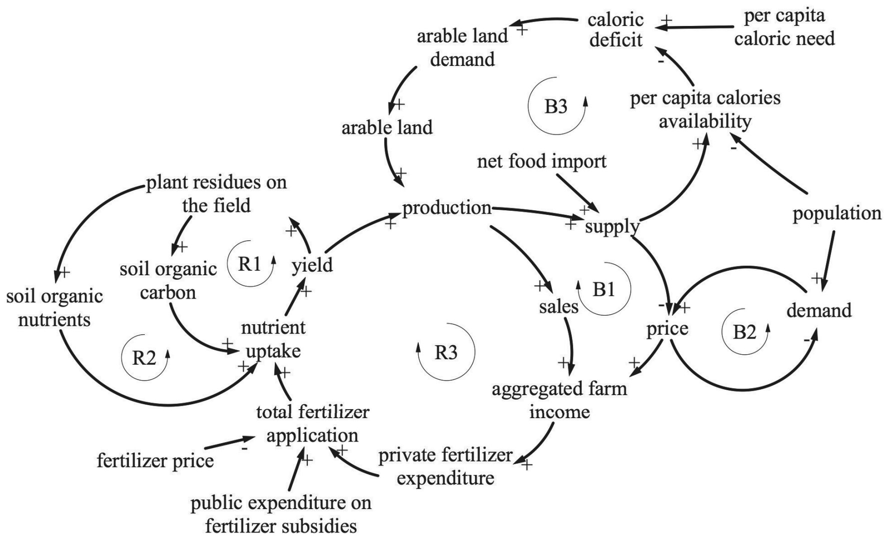

Figure 1. *Modeling framework for the Zambian plant production system. Notes: The arrows indicate causal relationships directed towards the arrowheads; a plus sign (+) denotes a positive polarity, indicating that the effect variable develops in the same direction as the cause variable. Similarly, a minus symbol (−) denotes a negative polarity, indicating that the effect variable changes in the reverse direction of the cause variable; A circular chain of causal relationships builds a feedback loop that is labeled with its polarity R (indicating self-reinforcing behavior) or B (indicating balancing behavior); the following feedback loops are represented: R1: reinforcing soil organic carbon loop; R2: reinforcing soil organic nutrients loop; R3: reinforcing sales loop; B1: balancing supply loop; B2: balancing demand loop; B3: balancing land adjustment loop; note that these feedback loops represent the fundamental processes of the framework. The complete simulation model used for the analysis contains additional mechanisms for operationalization and is available under supplementary materials.*

The links between *yield* and *soil organic nutrients*/*soil organic carbon* complete the first two feedback loops captured in the modeling framework: the reinforcing soil organic carbon loop (R1) and the reinforcing soil organic nutrients loop (R2). These two loops are self-reinforcing in nature and can either accumulate or deplete *soil* *organic carbon*/*nutrients*, depending on their current states. For example, an increase in *soil organic carbon* will lead to higher *nutrient uptake* rates and subsequently higher *yields*. In turn, higher yields will leave higher amounts of biomass on the field, which will add more organic carbon to the soil. Like the individual links that create the feedback loops, the feedback mechanisms as a whole are grounded in literature (e.g., [30]).

3.2 Supply and Demand Dynamics

Another section of the framework represents agricultural markets. Micro-economic theory in general and agricultural economics in particular assumes that market mechanisms equilibrate supplied and demanded quantities through price setting [26,27]. Unlike these standard approaches, the dynamic approach allows for disequilibrium through the accumulation of inventory stocks, which are implicitly incorporated in the market supply [28].

Domestic *supply* thus equals the sum of the domestic *production* and *net food imports* (food imports minus food exports), where domestic *production* equals the multiplication of average *yields* and *arable land* (the area on which food is produced). The links between these variables have positive polarity (Figure 1). Aggregated domestic food demand depends on the development of population, income, and food prices [27] (p. 302). The link between *population* and food *demand* has positive polarity whereas the link between *prices* and *demand* is negative (see the right-hand side of Figure 1). The effect of income on food demand is implicitly assumed to be constant and therefore omitted because population growth is the main driver of food demand in fast growing societies [27]. Food *supply* and *demand* affect food *prices* in reverse directions [26]. The link between food *supply* and *prices* has negative polarity, indicating that higher quantities of supplies lead to lower prices. By contrast, the link between food *demand* and *prices* is positive because higher *demand* leads to higher *prices*. Higher prices lead to higher farm incomes [26] and therefore the link between food *prices* and *aggregated farm income* is assumed to be positive. In turn, a higher income leads to higher expenditure on goods [26], and therefore the link between *aggregated farm income* and *private fertilizer expenditure* is assumed to be positive.

The additional variables and links create two feedback processes: the balancing supply feedback loop (B1) and the balancing demand feedback loop (B2). Both feedback loops not only consist of well-documented individual links but also appear as a whole in dynamic commodity market literature (e.g., [17,28]). Both balancing feedback loops cause prices to adjust until the market reaches equilibrium when the supplied quantity equals the demand quantity.

3.3 Self-Consumption and Land Dynamics

Many Zambian farmers produce food partly for subsistence [31] and sell the rest. Aggregated farm income therefore depends on food prices and the quantities sold by farmers. This mechanism is captured in the center of Figure 1 by the positive link between *sales* and *aggregated farm income*. The *sales*, in turn, are assumed to be positively influenced by the proportion of the *production* quantity that is sold. The introduction of sales to the framework in Figure 1 completes another feedback loop: the reinforcing sales loop (R3). This feedback mechanism self-reinforces the current trajectory of aggregated farm income. However, aggregated farm income is also part of the balancing supply loop that may counteract the reinforcing sales loop (R3).

Allocation of land is another crucial mechanism in food production systems. Land plays a central role in determining production in the analyses of the dynamic interactions between FSPs, SOM, and food production. Although land allocation has various determinants [32], de Vries [33] found that the root of land use change has its origins in the quest for food, fodder, and fibers. To capture this mechanism, I have introduced the variable *caloric deficit* in the upper part of Figure 1. *Caloric deficit* is the difference between the calories physically needed and the calories available from food supplies. The deficit increases if the *per capita calories available* decrease. An increasing food deficit is assumed to have an increasing effect on *arable land* through the intermediate variable *arable land demand*. These links create another feedback mechanism: the balancing land adjustment loop (B3). Similar to the balancing supply loop (B1), the balancing land adjustment loop (B3) works to equilibrate supply and demand by adjusting the arable land stock to its desired level. However, whereas the balancing supply loop (B1) operates in the short term, the balancing land adjustment loop (B3) works in the long term (cf. the capacity loop discussed by Meadows [28]).

3.4 Summary

Figure 1 represents a summary of the analyzed framework. Each link and feedback process presented above has been derived from the literature. The novelty of this study arises from the integration of these mechanisms and the analysis of their dynamic interaction. Undoubtedly, the framework could be more complex than the one presented in Figure 1. However, I focused on capturing the structural complexity by integrating just the core elements of food production systems for analyzing the interaction between FSPs, SOM, food production, and food availability. Thus, the framework is as large as needed and as small as possible to represent central mechanisms. Further research could build on this structure by incorporating additional theories and mechanisms.

4. Model Specification

The framework presented above has been specified into a mathematical model for analyzing the dynamic interaction between FSPs, SOM, maize production and maize availability. Key equations are presented in this section. It should be noted that the full model includes additional mechanisms that are needed for completeness. Because they are not of central importance for determining the overall model behavior, they have not been mentioned in the descriptions above and below. Different sectors of Zambia’s food production system are represented in the model according to their importance in terms of caloric contribution of available food: the interactions in the maize sector are fully represented, the interactions in other plant production sectors are partly integrated, and animal production is summarized for completeness. The full model was specified using Vensim software [34] and is available under supplementary materials.

4.1 Fertilizer, Yield and Soil Dynamics

The mathematical representation of fertilizer use, maize yield and soil dynamics focuses on the most crucial yield-limiting factors, which are nitrogen and water in Zambia [12,35]. Total fertilizer application is a major source of nitrogen and depends on public and private expenditure. Thus, mathematically, total fertilizer application can be defined as

$$TFA = \frac{(FS + PFE)}{FP} \tag{1}$$

where TFA is the total fertilizer application, FS denotes public expenditure on fertilizer subsidies, PFE represents private fertilizer expenditure and FP is the average fertilizer price. Another source of nitrogen for plant growth is bound up in the SOM stocks. The change of elements in SOM stocks can be formulated using a first order differential equation [24]:

$$\frac{dE}{dt} = I(y) - \frac{E}{tmin} \tag{2}$$

where E is the amount of organic element per hectare and $I(y)$ represents inputs of the organic element expressed as a function of maize yield y using the formulation in the IPCC guidelines [36]. The last term of Equation (2) represents the mineralization of the organic nutrients with $tmin$ being the average mineralization time [24]. The two elements E represented in the model are nitrogen (N) and carbon (C). N is included for its crucial role in determining yields and C is included to represent SOM.

Subsequently, nutrient uptake by plants is expressed as

$$x1 = \left(\frac{TFA}{AL} + \frac{N}{tmin}\right) \times f(C) \tag{3}$$

where x_1 denotes the nitrogen uptake by plants and AL represents arable land. Within the first brackets, available nitrogen is calculated as the sum of nitrogen fertilizer application per hectare and mineralized organic nitrogen. The actual nitrogen uptake is a fraction of the term in the first brackets determined by a linear function of C.

Thus, maize yield is obtained by using a Mitscherlich-Baule production function [25]:

$$y = A \times (1 - 10^{-c1 \times x1}) \times (1 - 10^{-c2 \times x2}) \tag{4}$$

where y is the average maize yield, A the yield plateau representing a potential yield under perfect factor availability, c_1 and c_2 are context-specific constants and x_1 and x_2 represent factor uptakes (x_1 nitrogen and x_2 water).

4.2 Supply and Demand Dynamics

Supply results from domestic production and net imported food quantity, and is expressed as

$$S = Prod + NetImp = (AL \times y) + (Imp - Exp) \tag{5}$$

where *S* is the supplied quantity, *Prod* represents the domestic production, and *NetImp* is the net food imports, comprising imports (*Imp*) and exports (*Exp*). Demand depends on the population's physical needs, people's preference for a product, and the food price:

$$D = Dref + g(Pop) + h(P) \tag{6}$$

where *D* refers to the demanded quantity. *Dref* represents a reference demand quantity that is adjusted for population (*Pop*) development and prices (*P*). In turn, the price is determined by adjusting a reference price to disequilibria in supply and demand. Mathematically, price is calculated as follows

$$P = \left(\frac{S}{D}\right)^{\varepsilon} \times Pref \tag{7}$$

where *P* denotes the price, *Pref* is an equilibrium reference price, and ε a sensitivity parameter determining the strength of the price adjustment in the case of an imbalance in supply and demand.

4.3 Land Dynamics

The driver of land use change is average per capita calories availability, which is mathematically conceptualized as

$$PCCA = \frac{(S - NFP) \times kcalM}{Pop} \tag{8}$$

where *PCCA* denotes per capita calorie availability, *NFP* is plants produced for non-food purposes such as fodder or fiber, *kcalM* is a multiplier to express food quantities in kilocalories and *Pop* denotes the country's total population. The relative difference between the caloric need and *PCCA* determines, among other variables, the land conversion rate:

$$\frac{dAL}{dt} = \min\left(\frac{PCCN - PCCA}{PCCA} \times AL, mCR\right) - CROL \tag{9}$$

where *PCCN* is the per capita calorie need, *mCR* denotes a maximal conversion rate and *CROL* represents the conversion of *AL* into other land which is used for settlements and roads. The min-function enforces the choice of the smaller argument between what is desired (first argument in the brackets) and what is maximally possible (second argument in the brackets).

Private fertilizer expenditures are assumed to be a share of income:

$$PFE = Inc \times ShF = (P \times Sales) \times ShF \tag{10}$$

where *PFE* is the private fertilizer expenditure, *ShF* the share of aggregate farm income that is spent on fertilizer purchases, and *Inc* is the aggregate farm income. The latter consists of *P* multiplied by the quantity sold (*Sales*).

5. Calibration, Validation and Past Trajectories

The above-described simulation model runs from 1984 to 2050. To capture long-term phenomena, the simulation model needs anchoring in a long-term reference period. Thus, the model was calibrated for Zambia using continuous annual data for 28 reference years. The reference period is 1984–2011, corresponding to the time when the data quality of central variables started to be reliable [22], and when reporting of major uniform data sources ceased (Table 1). Further time series were used as exogenous model inputs for the past and their prescription served as scenarios for the future in cases where parameters could not be assumed constant over the analysis period. Constant parameters were obtained through triangulation procedures, including a literature review, data analysis, and indirect optimization. An overview of the key constants is presented in Table 2.

Table 1. *Data series used in the simulation process.*

Data Series	Usage	Sources
Population	Model input & scenario	[37]
Maize yield	Calibration	[38]
Maize production	Calibration	[38]
Arable land	Calibration	[38]
Maize trade	Model input & scenario	[20]
Land use	Calibration	[39]
Maize prices	Calibration	[22,40–42]
Fertilizer use	Calibration	[39]
Fertilizer prices	Model input & scenario	Estimated from [42]
Fertilizer subsidies	Model input & scenario	[22,43–46]
Precipitation	Model input & scenario	[47]
Manure application	Model input & scenario	[48]
Soil organic matter	Calibration	Qualitative, [49]
Maize sales	Calibration	[22,50]

***Table 2.** Parameter values for key constants in the model.*

Constant	**Value**
c_1 (yield coefficient of nitrogen)	4.03 (ha×year/ton)
c_2 (yield coefficient of water)	0.004 (year/mm)
ε (price sensitivity to supply-demand imbalances)	−0.86
P_{ref} (reference producer maize price)	55 (ZMK/kg)
t_{min} (mineralization time of SOM)	31 (year)
PCCN (per capita calories need)	2200 (kcal/person/day)
Plant residues removed from field	70 (%)
Seed requirement	0.03 (ton/ha/year)
Demand sensitivity to consumer price	−0.1

The model was validated through structural and behavioral tests [18]. This article seeks to understand observed dynamics based on the underlying system structure. It is crucial in this context that the structure is a valid representation of the real processes that significantly contribute to creating the dynamic behavior. Structural validation was achieved through logical, theoretical, empirical, sensitivity, and boundary tests, which were continuously applied throughout the whole modeling process. The high number and the long, qualitative and repetitive nature of these tests meant it was not possible to present the results in an article such as this one. I therefore merely state that the model was found to be structurally robust, in part due to the theory integration described above, which is the result of extensive structure test procedures. Behavioral validity tests mainly focus on an adequate representation of general behavior patterns and to a much lesser extent on a precise match between model output and real data (in contrast to other modeling approaches, where this point-to-point match is crucial). Behavioral validity was achieved through structure-oriented behavior and behavior pattern tests. Figure 2 shows a comparison of historical data and the simulated trajectory of maize yield. The variable maize yield is suited for behavior and calibration tests because it is endogenously calculated, it is part of many feedback loops, and the data quality is reliable. Short-term variations in maize yield are subject to various factors [51], of which only the two main factors, nitrogen and precipitation, are captured in this model. Hence, the model does not control for all of the short-term variations. Instead, it focuses on and adequately represents the long-term trend of empirical maize yield trajectories, which is confirmed by the results of the Theil statistics (Table 3). Theil statistics decompose the overall root mean square percentage error (RMSPE) into three types of errors: bias error (U^M), unequal variation between data and simulation error (U^S), and unequal co-variation error (U^C). The error here (as presented in Table 3) is unsystematic because it concentrates in U^C and the study focuses on long-term trends [52].

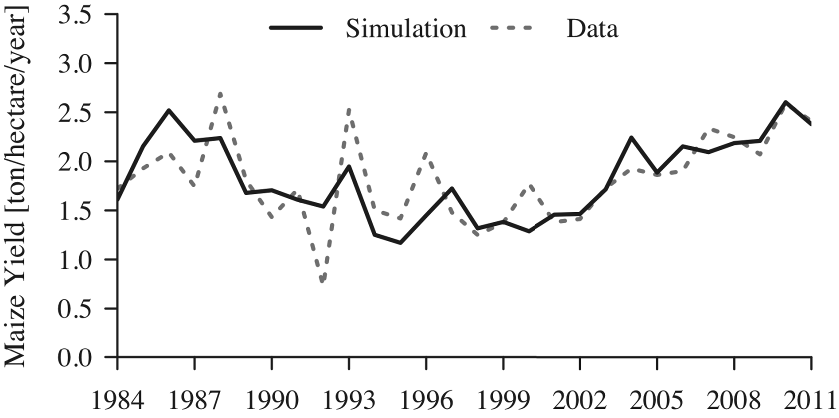

Figure 2. *Simulated trajectories of Zambia's maize yield compared to historical data (1984–2011).*

Table 3. *Theil statistics to compare simulated trajectories with data for maize yields.*

RMSPE	U(M)	U(S)	U(C)	R2
0.254	0.000	0.014	0.986	0.521

The past behavior in Figure 2 can be split into three phases. In the 1980s low fertilizer prices and partly high FSP expenditures supported the reinforcing sales loop (R3) in providing high maize yields and high maize availability. Through the reinforcing soil organic carbon loop (R1), SOM stocks increased (at low levels) and reinforced the high yields. The 1990s and early 2000s were characterized by high fertilizer prices, relatively low FSP expenditures, and an increasing area allocated to maize, resulting in lower applications of fertilizer per hectare and therefore lower yields. Consequently, SOM stagnated. Thus, the feedback loops that helped to increase maize yield in the 1980s were weak in the 1990s. Additionally, the growing population increased and through the balancing demand loop (B2) also the maize demand and maize prices increased. Consequently per capita maize availability dropped during the 1990s. As a reaction to the low maize availability, the 2000s were characterized by a further increase in maize area and increased FSP expenditures. In addition, fertilizer prices decreased again. These mechanisms strengthened the balancing land adjustment loop (B3), as well as the R1 and R3 loops, resulting in higher maize yields and production. However, per capita maize availability remained low during the 2000s because the population grew fast and maize production could not keep pace with the population increase.

Thus, a combination of endogenous mechanisms and exogenous variable trajectories accounts for the past behavior of Zambia’s maize production system. In the following section I provide an in-depth analysis of possible future maize production system outcomes under different FSP expenditure scenarios. For the following analysis I assume that the environment of the food production system remains sufficiently stable for the endogenous dynamics of the system not to be overruled by external influences.

6. Model Analysis

The model has been intensively analyzed to test the range of behavioral outcomes under varying parameter and policy assumptions. In this section I present a few experiments to highlight the most interesting outcomes. The model analysis runs from 2011 to 2050, which is long enough to study long-term social and environmental processes in the food production system. Although the analysis is projected into the future, it is not my intention to make point predictions. Instead, I aim to understand the fundamental mechanisms and behavior patterns of the food production system in response to the FSPs.

Simulating the future requires scenario assumptions about the value of exogenous parameters. If the values of a parameter fluctuated around a mean in the past, I calculated the average parameter value of the calibration period and applied it to the future (e.g., fertilizer price). However, this procedure is not reasonable for certain parameters because they show an increasing or decreasing past trend that will most likely extrapolate into the future. For example, population represents a major driving force in the food production system and the population is expected to grow continuously over the simulation period. I therefore applied an exogenous population scenario based on UN estimates [37], which project that the Zambian population will increase from 13.6 million people in 2011 to 44.2 million people in 2050. Further details about the scenarios of other variables are available in the fully specified Vensim model in the supplementary materials.

In the remaining part of this section I present eight simulation experiments for varying FSP expenditure patterns and evaluate the system's outcome using the variable maize availability. Maize availability is suitable for this purpose because it is a major food system outcome, FSPs specifically aim at improving it, and when expressed on per capita basis maize availability allows for the growing population to be taken into account. A summary of the experiments' setting is presented in Table 4.

__Table 4.__ Policy assumptions of the simulation experiments.

EXPN	FSPE	FSPD	SOMP	Description
E1	0	Constant	No	Base run: no policy in place
E2	1.98^{10}	Constant	No	Medium FSPE[1]; Extrapolation of the status quo
E3	1.98^{10}	Drop in 2030	No	Medium FSPE; FSP removed in 2030
E4	4.50^{10}	Constant	No	High FSPE
E5	4.50^{10}	Drop in 2030	No	High FSPE; FSP removed in 2030
E6	1.98^{10}	Constant	Yes	Medium FSPE & addition of SOM
E7	1.98^{10}	Drop in 2030	Yes	Medium FSPE, addition of SOM; FSP removed in 2030
E8	4.50^{10}	Linear fall	Yes	High FSPE, addition of SOM; FSP gradually removed

Notes: EXPN = experiment number; FSPE = fertilizer subsidy program expenditures (ZMK/year); FSPD = fertilizer subsidy program expenditure development; SOMP = Soil organic matter policy in place; FSP = fertilize subsidy program; SOM = soil organic matter; [1] Average FSP expenditure in the period 1984–2011.

6.1 Analysis of Mechanisms

Experiment 1 (base run without FSP expenditure) provides a useful introduction into the analysis (Figure 3). The growing population creates an increasing demand for maize, and the balancing supply loop (B1) and the balancing land adjustment loop (B3) try to adjust maize supply to the new levels of demand. However, low farm endowment and the missing FSPs hinder both loops from fully balancing supply and demand. Hence, maize availability first decreases and then stays around 725 kcal per person per day, which is insufficient compared to the estimated requirement of 1100 kcal per person per day.

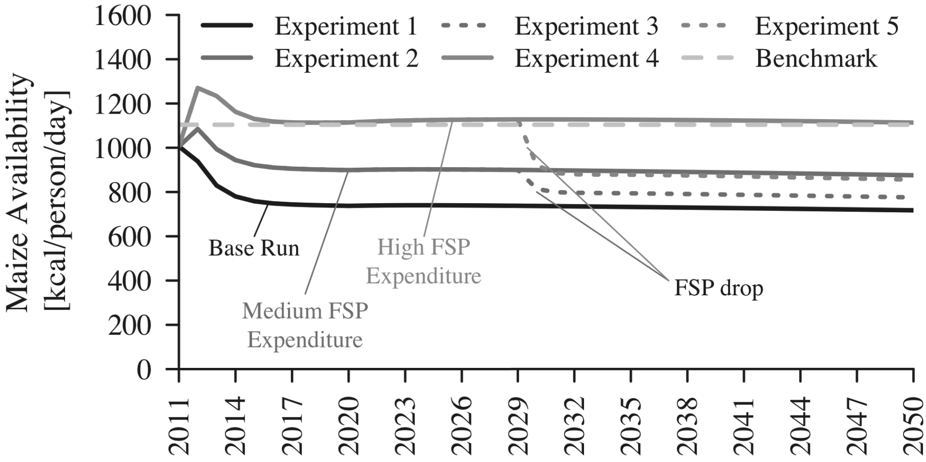

Figure 3. *Simulation results of maize availability for five experiments under varying fertilizer subsidy program (FSP) scenarios for the period 2011–2050.*

Whereas experiment 1 without FSP expenditure results in low maize availability, experiments 2 and 4 test the impact of increasing levels of FSP expenditure. Simulation results suggest that FSPs strengthen both the reinforcing sales loop (R3) and balancing supply loop (B1) and thus the ability of the system to balance maize supply and demand. Through the sustained external subsidy input, maize production and maize availability experience an enduring increase, and if FSP expenditures are high enough maize availability will even reach the desired levels (in experiment 4). However, the success of FSPs in terms of maize availability has a downside, as experiments 3 and 5 reveal. Both experiments start with levels of FSP expenditure that are identical to those in the previous experiments 2 and 4. The only difference is that FSP is completely abandoned in the year 2030 in experiments 3 and 5. As a reaction to the FSP withdrawal, maize availability quickly and enduringly drops, but still settles above the level of no-subsidy experiment 1. Thus, a first insight is that FSPs constitute an instrument capable for maize availability steerage. However, the immediate drop in maize availability after the FSPs' removal shows that the steerage potential is limited to the short-term.

The immediate response of maize availability to changes in the subsidy level happens because the reinforcing sales loop (R3) and balancing supply loop (B1) do not include major time delays. However, these two feedback loops are insufficient to understand why maize availability in experiments 3 and 5 (in which FSPs are initially applied and later dropped) settles above the no-subsidy case in experiment 1. Instead, soil dynamics play a central role, as shown in Figure 4. During the period of subsidy application, SOM stocks are built up though higher yields and biomass production. In addition, the reinforcing soil organic carbon and nitrogen loops (R1 and R2 loops) reinforce an upward behavior and accumulate SOM until external mechanisms stabilize the stock levels (R3 and B1 loops). If the subsidy program is abandoned, the inert SOM stock stays above the level of the no-subsidy case in experiment 1. Experiments 3 and 5 therefore result in higher long-term maize yields, production levels, and availability compared to experiment 1. Thus, a second key finding is that the FSP has a slow, positive impact on SOM, although the increase in SOM is moderate.

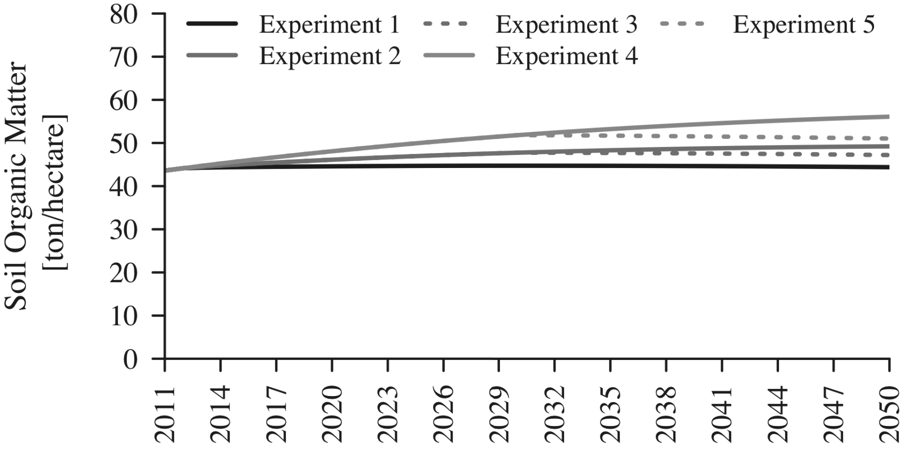

Figure 4. *Simulation results of soil organic matter for five experiments for the period 2011–2050.*

Having understood the crucial role of SOM stocks, I tested the impact of a new policy that directly addresses SOM accumulation (through incorporation of additional plant residues to the soil). Simulation results suggest that the policy, in addition to FSPs, has a beneficial impact on maize availability in the long run (experiment 6 in Figure 5). Because the new policy directly strengthens the reinforcing soil loops (R1 and R2) and allows a gradual SOM accumulation over time, maize availability steadily increases. The beneficial trend even endures on a lower level if FSPs are removed (as in experiment 7). Thus, a third key finding is that policies directly targeting SOM stocks are beneficial for long-term maize availability and enhance the system's resilience to changes in FSP expenditure level because the increasing trend will endure even if FSPs are completely removed. In this sense, building up SOM stocks is a more sustainable policy than FSPs.

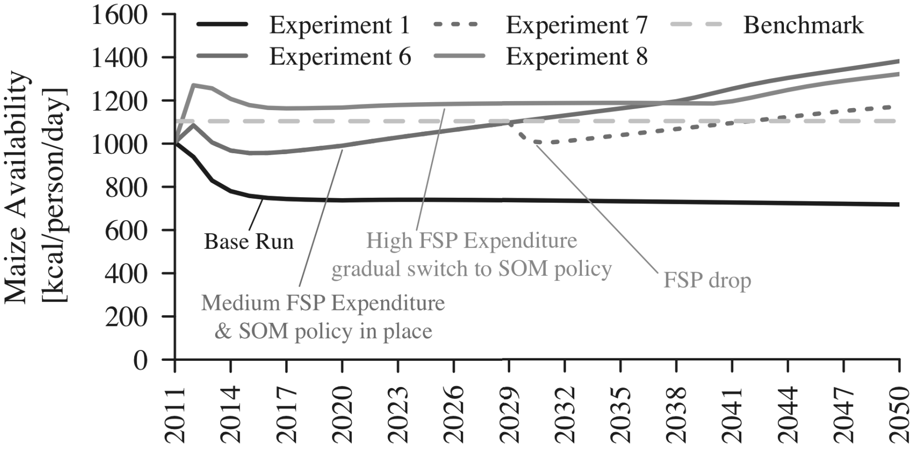

Figure 5. *Simulation results of maize availability in four experiments under varying fertilizer subsidy program (FSP) and soil organic matter (SOM) accumulation policies for the period 2011–2050.*

Given the short-term benefits of the FSPs and the delayed effect of SOM policies, experiment 8 combines the two approaches (Figure 5). In experiment 8, fertilizer subsidies are initially high and then continuously reduced before they completely expire in year 2040. Simulation results suggest that the combination and sequencing of the two instruments is a viable strategy to enhance maize availability and simultaneously abandon the subsidy program.

6.2 Analysis of Key Variables

The long-term impacts of the different policy assumptions on target variables are summarized in Table 5 and confirm the analysis of the above-described mechanisms. FSPs increase fertilizer use if applied enduringly. However, after FSP removal the increasing effect on fertilizer use is very little. FSPs also have an increasing effect on SOM stocks, but, policies directly targeted at SOM stocks show a higher effect, even if FSPs are removed. Subsequently, and due to the important role of SOM, also production variables, such as maize yield, maize production, and maize availability, are highest under a policy that directly addresses SOM. To a lesser extent, also FSPs have the potential to increase the values of these production indicators if they (the FSPs) are applied enduringly. However, the production indicators dropped in experiments in which FSPs were removed.

Table 5. *Simulation values of key variables in 2050 for the different experiments.*

EXPN		**Fertilizer Use**	**Soil Organic Matter**	**Maize Yield**	**Maize Production**	**Maize Availability**
E1	Value	28,916	44	1.5	3.8	717
E2	Value	44,061	49	1.9	4.6	876
	Change to E1	+52%	+11%	+21%	+22%	+22%
E3	Value	30412	47	1.7	4.1	776
	Change to E1	+5%	+6%	+8%	+8%	+8%
E4	Value	65617	56	2.4	5.9	1114
	Change to E1	+127%	+26%	+53%	+55%	+55%
E5	Value	32468	51	1.8	4.5	856
	Change to E1	+12%	+15%	+19%	+19%	+19%
E6	Value	47255	69	2.7	6.4	1382
	Change to E1	+63%	+56%	+78%	+69%	+93%
E7	Value	40545	66	2.5	6.2	1171
	Change to E1	+40%	+49%	+62%	+63%	+63%
E8	Value	37833	71	2.7	6.3	1322
	Change to E1	+31%	+60%	+74%	+68%	+84%

Notes: EXPN = experiment number; fertilizer use in tons nitrogen/year; soil organic matter in tons/ha; maize yield in tons/ha/year; maize production in million tons/year; and maize availability in kcal/person/day.

7. Discussion and Conclusions

In this article, I have integrated relevant theories into a simulation model to investigate both the short-term and long-term impacts of Zambia's fertilizer subsidy program (FSP) on the country's maize production system. The analysis of policy scenarios suggests that FSPs are a viable means to enhance short-term fertilizer use, productivity, maize production, and maize availability. However, the program's long-term enhancement effect on maize availability will be limited once FSPs have been removed, because it fails to adequately build up soil organic matter (SOM) levels. SOM is a long-term leverage point and an important source of resilience in the maize production system. Alternative policies that add organic material to the soil directly target this leverage point and are more suitable than FSPs for enhancing long-term maize availability. These findings contribute in manifold ways to the current debate about FSPs in Zambia.

The findings that FSPs are effective for increasing fertilizer use and boosting maize production in the short-term coincide with other studies' findings (e.g., [4,53]). However, the short-term orientation of FSPs makes the maize production system in general and maize availability in particular vulnerable to changes in the government's FSP expenditure and changes in fertilizer prices. This restricts the policy's sustainability and indicates the need for alternative policies that strengthen the system's resilience.

In common with Jayne and Rashid [2], my study finds that unfavorable and inert soil properties are a core factor for explaining why FSPs lack long-term efficiency. However, based on the integration of relevant theories and the specification of causal links, the findings here relativize the widespread agreement that a substantial increase in inorganic fertilizer use is necessary to improve soil fertility [3,8]. Although I have found some increase in SOM levels under FSPs, other policies directly targeting SOM have shown a much higher impact on relevant organic nutrient stocks and thus increased the system's sustainability and resilience to changes in FSP expenditures. However, building up SOM stocks takes considerable time and the maize production system reacts to such policies in the long-term. Therefore, the two policy approaches are complementary, which has implications for policy formulation.

To reduce the maize production system's dependence on FSP expenditure and to reduce other, aforementioned drawbacks, abandoning FSPs seems a reasonable strategy. To avoid drastic drops in maize availability, I suggest combining and sequencing the two policy approaches: while building up a long-term strategy for increasing SOM stocks, FSPs could gradually be phased out. Abrupt changes in maize availability are avoided by such a gradual transition, which might increase the political feasibility of abandoning FSPs. The study design enables an understanding of dynamic mechanisms on a broader level, but its capability to advise on a detailed implementation level is limited. Hence, other research addressing the implementation issues of SOM policies, such as by Place et al. [54] or by Vanlauwee [55] might complement the present study. Further research should also closely investigate costs, benefits and opportunity costs of such a gradual policy change. Special attention should be devoted to the state budget through the initial phase of transition when FSP expenditures are still high and simultaneous investments in extension services to implement soil policies are required.

Managing soils is generally complex [11]. Increasing SOM levels is a stock management problem and includes accumulation processes, which are subject to misperception [56]. Making the SOM accumulation processes explicit by visualization is a possible means to increase understandability of soil management. Based on the simulation approach taken in this article, Figure 6 translates Equation (2) into a visual representation where SOM is displayed by a rectangle that symbolizes a reservoir in which SOM accumulates. The forces that add and withdraw SOM from the reservoir—the addition of organic material to the soil and mineralization—are represented by arrows that symbolize the flows into and out of the SOM stock. Because the mineralization magnitude depends on the SOM stock level (Equation (2)), the mineralization process tends to bring the SOM level to a long-term dynamic equilibrium, depending on the inflow [29]. Thus in practice, SOM stock levels are manageable through the inflow, which can be controlled through the application of organic material from various sources, such as plant residues, compost, and manure. SOM stock levels only increase if the inflow (addition of organic material to the soil) is larger than the outflow (mineralization). Because both processes work simultaneously, SOM accumulation advances slowly, and output results such as higher yields may occur only in the long term. However, such output results are sustainable in the sense that once SOM has accumulated it does not degenerate quickly, due to the long mineralization time (Equation (2), Table 2). In addition to the these output results, higher SOM levels increase the maize production system's resilience towards rainfall variation, which is a crucial property with regard to climate change.

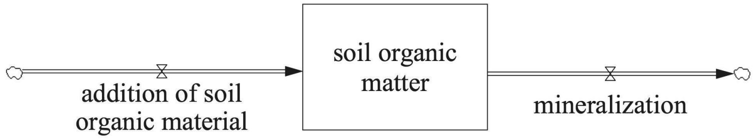

Figure 6. *Visual representation of the soil organic matter (SOM) stock accumulation process. The box indicates a stock that accumulates over time and the arrows represent flows that change the stock level over time.*

This study has taken an approach that goes beyond mere statistical analysis to add a new perspective on the FSP debate, as suggested by Jayne and Rashid [2] and Crawford et al. [15]. I have integrated existing theories and made their connections explicit by formulating a fully specified simulation model. The results indicate the potential of such an approach. By structuring existing knowledge in a broader and dynamic context, conventional assumptions can be challenged and refined in a "virtual playground". While this study has focused on the core production processes, future work could build on this by adding additional mechanisms. For example, poverty could be represented in more detail because its reduction is an underachieved goal of FSPs. Overall, this study has demonstrated the usefulness of feedback-based simulation tools and can be a stepping-stone for future work that aims to evaluate the sustainability of FSPs and other policies from a broader perspective.

Supplementary Materials: The following materials are available online at www.mdpi.com/2071-1050/8/10/1036/s1, Model M1: A folder with the Vensim model file, the data set needed for simulation, and the eight experiments. A detailed description and conceptual foundation of each variable is available in the comment field of the variables within the model file.

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Article 2

Why do some food availability policies fail? A simulation approach to understanding food production systems in south-east Africa

Article 3

Cournot markets in the field: Dynamic decision-making in non-standard markets

Cournot markets in the field: Dynamic decision-making in non-standard markets

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Abstract

The Cournot economic model is very useful for representing atomized markets in laboratory experiments. Ideally, such experiments are designed following a set of conditions in order to use the model properly. However, non-standard markets and procedural concerns make it impossible for standard conditions to be adhered to in some cases. One such case is the context of rural Africa, where economic objectives of market participants differ from profit maximization, where experiments are typically conducted outdoors and where subjects have low degrees of literacy and familiarity with computers. This article describes a case study that investigated dynamic decision-making of Zambian smallholder farmers by adjusting the standard conditions of Cournot experiments to the field context of rural Africa. Both, the empirical experience from applying the proposed experimental design, as well as the insights gained based on the analysis of the experimental data highlight the usefulness and feasibility of Cournot experiments under non-standard conditions. Thus, the authors argue that the Cournot model can be used under non-standard conditions as a means to explore decision-making in contexts in which non-standard markets and procedural limitations do not permit the use of standard conditions. Furthermore, and based on the case study, the article develops initial guidelines for further studies in contexts with similar characteristics.

Keywords: Cournot experiment, standard conditions, dynamic decision-making, system dynamics, food security, smallholder agriculture, rural Africa

1. Introduction

Laboratory experiments have long been used in the field of system dynamics to study dynamic decision-making in controlled settings (for an overview, see Arango et al., 2012). Laboratory experiments help identifying the decision rules or heuristics that people use to explain observed problematic behavior in systems, such as overshoot and collapse of natural resources (e.g., Moxnes, 2004) or oscillations in inventory-distribution systems (e.g., Sterman, 1989). When it comes to modeling market competition, some real-life markets can be represented with the Cournot oligopoly model.

The behavioral market theory behind the Cournot oligopoly model (Cournot, 1838) helps understanding the performance of a number of independent firms that compete with each other in a market through the production of a certain good. Although a number of authors have criticized the assumptions in and solutions from the Cournot model (e.g., Theocharis, 1960; Puu, 2008), the oligopoly model's adequacy for representing different types of markets is still regarded as valuable. Cournot market experiments involve several players competing to maximize a defined goal (e.g., revenues, profits, and market share) in a given market. In system dynamics, the model has been applied, for example, by Arango and Moxnes (2012), Arango et al. (2013) and Lara-Arango (2014). Their studies demonstrated that Cournot market experiments can generate valuable insights, such as the endogenous nature of commodity cycles and the effect of specific institutions on market performance, such as mothballing or capacity mechanisms.

Cournot market experiments are based on a series of fairly strict assumptions that are summarized in the standard conditions[1] that we describe in detail in the next section. From an experimental perspective, standard conditions can be thought of as a benchmark for comparisons when users vary one of the conditions. However, complying with the conditions limits the use of Cournot market experiments to conventional laboratory experiments and to standard markets, i.e., markets where players share the same objective functions as the firms in the Cournot oligopoly model, or where players have constant budgets.

These idealized conditions are often not met in reality. For example, market participants' objective functions differ from pure profit maximization in markets where local history and status interact with global and international processes (e.g., Berkes et al. 2003). It also differs from pure profit maximization in precarious situations where market participants need to focus on covering the most basic needs before optimizing their production activities according to economic logic, as for example in humanitarian operations (e.g., Carbonnier 2015). Lastly, market participants might not only maximize profits in situations where the producers are at the same time important consumers of the product as for example in small-scale agriculture in developing countries (Umar, 2014). Besides non-standard markets, i.e., markets with uncommon objective functions, there are other circumstances that require deviations from the standard conditions, such as procedural limitations regarding the feasibility or desirability of conducting conventional, fully computerized laboratory experiments. Procedural limitations can be rooted in lack of available infrastructure, participants' educational and cultural background, desire to avoid interpretations of a fully computerized laboratory experiment as a gaming session, or desire for making the experimental setting as close to the real-world decision making context as possible (Harrison and List, 2004).

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[1] According to Huck et al. (2004), the standard conditions for Cournot experiments are: fixed groups; fixed number of periods; products are perfect substitutes; cost symmetry across firms; no communication between subjects; complete information about the payoff function; information about own profits, market supply and price is available to the subjects; economic framing of the experiment.

We hypothesize that a Cournot market experiment can be a useful tool to study decision-making in cases of non-standard markets and procedural limitations, even though that implies a substantial deviation from more than one standard condition. We explore this hypothesis by using a case study about smallholder farming in developing countries. Farmers in developing countries in general and in sub-Saharan Africa in particular face the challenge of considerably increasing food production for their growing and more demanding populations, while also rebuilding and maintaining the natural resource base (e.g., Campbell et al., 2014; Garnett et al., 2013; Pretty et al., 2011; Tilman et al., 2011). Smallholder farmers, who make up the vast majority of farmers in sub-Saharan Africa, struggle with combined food insecurity and natural resources based poverty traps (Stephens et al., 2012). This makes sustainable intensification particularly challenging. In this context, understanding how farmers make and adjust their decisions regarding food production and natural resource use constitutes an important precondition for the design and implementation of effective and sustainable intensification strategies.

In the case of sub-Saharan African farmers, dynamic decision-making about the choice of sustainable intensification practices deviates from the standard conditions in Cournot market experiments in two main ways. First, smallholder farmers who struggle with food security focus on maximizing their production rather than their profit (Umar, 2014). Second, it would be impractical to conduct a conventional laboratory experiment with smallholder farmers in rural areas in sub-Saharan Africa for a variety of reasons (low formal educational background of smallholder farmers, low levels of familiarity with analytical thinking in general and interaction with computers in specific, limited availability of infrastructure such as computer networks or electricity). To the best of our knowledge, there are no clearly defined guidelines for addressing such contexts.

In this article, we report a case study about dynamic farm decision-making in Zambia for which we had to adjust the standard conditions in several ways to match the local context. We focus on a budget allocation decision between two expenditure alternatives: a short-term fertilizer application strategy and a long-term soil improvement strategy. Our experiment is based on a system dynamics model developed by the second author of this article (Gerber, 2016). The model captures the essential features of the commodity market with which smallholder farmers interact. We used Cournot's market principles as a basis for our experimental design and complemented it with principles from field experiments in order to be able to carry out an exploratory study that would allow us to understand better how Zambian farmers make use of their budgets. Furthermore, this specific case is illustrative for a wide range of cases related to sustainability and production. Such cases occur when production decisions not only have economic consequences in the short-term but also wider sustainability impacts in the long-term, e.g., in energy, agri-food, renewable (water, fish, forests), as well as non-renewable resource systems (de Vries, 2013).

The outcomes of our exploratory study and the insights in terms of dynamic decision-making have been described in detail in a separate article (Gerber et al., 2017). Here, we focus on the methodological contributions of our experimental design. First, we contribute to the literature on the implementation and design of field experiments (Harrison and List, 2004). Second, we contribute to the debate on the importance of each of the Cournot standard experimental conditions, with respect to a specific problem (Huck et al, 2004). Third, we enrich the toolbox available to system dynamicists for studying dynamic decision-making in commodity markets under non-standard conditions and in a sustainability context. Based on our case study we propose initial guidelines for Cournot experiments under non-standard conditions. Fourth, and in addition to the scientific contribution of our experimental design, we found that farmers who participated in the experiments indicated that our approach is a viable means for interactive capacity building.

The remaining part of the article is organized as follows. The next section presents the standard conditions of Cournot experiments and the different types of field experiments. The third section describes an experiment conducted with Zambian smallholder farmers that frames Cournot markets as field experiments. The fourth section summarizes the results of the experiment and discusses the implications from diverging from the Cournot market experiment standard protocol. Finally, we present our conclusions in the fifth section.

2. Theoretical background

2.1 Cournot markets under standard conditions

Modern Cournot market experiments use the standard conditions proposed by Huck et al. (2004). In this section, we present each of the standard conditions and discuss their importance when running Cournot experiments.

Interaction takes place in fixed groups

Participants in experiments (subjects) who are randomly matched in every round of an experiment are not likely to generate high levels of collusion[2] (Holt, 1985). Lack of collusion implies that the Cournot-Nash equilibrium is a powerful predictor in these situations (Huck et al., 2001). However, real markets often consist of firms interacting with one another for long periods, which allows each of them to develop strategies based on the profiles of their competitors. Moreover, failure to consider such long-term interaction would imply that Cournot markets are only applicable when collusion is not possible (as is the case in randomly matched experiments). However, collusion is possible in practically every market. Thus, assuming there are fixed groups in Cournot markets (i.e., groups with the same subjects who interact within the market for the whole of the experiment's duration) is a standard condition and has often been found realistic.

Interaction is repeated over a fixed number of periods

Previous studies, such as the one conducted by Feinberg and Husted (1993), have shown that collusion is more likely to arise when Cournot games have a high continuation probability, meaning that they run for an indefinite number of rounds. In practice, however, even a few rounds can elicit collusion if other experimental factors

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[2] Collusion can be understood as the extent to which a group of individuals (or groups of individuals) agree to work together to achieve a common goal.

allow for it, such as fixed groups (Holt, 1985; Huck et al., 2001) and communication (Cason and Davis, 1995; Holt and Davis, 1990). Therefore, the importance of having a fixed number of rounds does not avoid collusion per se. Nevertheless, a fixed number of rounds is recommended because it allows the experimenter to make comparisons across treatments and with other experiments.

Products are perfect substitutes

Differentiated products lead to more complex competition, in which firms not only compete in terms of production and costs but also in terms of product-specific issues such as branding and pricing. In this more complex environment, factors such as subjects' experiences can make significant differences. Benson and Faminow (1988) found that experience in markets with differentiated products is a crucial for reaching equilibrium through tacit collusion. In order to avoid cofounding effects from variables such as experience, perfectly substitutable goods are assumed to be a standard condition in Cournot experimental markets.

Costs are symmetric

Asymmetries in costs lead to a more complex competition environment. Cost advantages are likely to give more market power, which in turn, will make the market more biased. In this regard, Mason et al. (1992) and Rassenti et al. (2000) show that asymmetries in costs often lead to significantly higher outputs than expected due to the players having cost advantages. Cournot markets tend to behave more like competitive markets than oligopolies when the number of players is roughly equal to or higher than four. In a competitive market, players with a cost advantage will exercise very little constraint when the market is flooded with products; they will have lower costs and will therefore be able to take a lower price than the other players can. Given this tendency by such players, the market will end up with a "higher than normal" output. Symmetric costs are a necessary assumption to prevent this bias. Therefore, symmetric costs are a standard condition in Cournot experimental markets.

There is no communication between subjects

Communication between subjects is likely to lead to high levels of collusion. Previous studies of posted-offer triopolies and Bertrand markets have shown that non-binding announcements often lead to higher prices (e.g., Cason and Davis, 1995; Harstad et al, 1998; Holt and Davis, 1990). Thus, a standard condition is that subjects do not communicate with each other.

Subjects have complete information about their own payoff functions

This point relates to the salience principle presented by Smith (1982), which is that, in order to develop solid decision-making rules, subjects need to know exactly what the consequences of their actions will be in terms of their reward. In other words, subjects need to know how their decisions will determine their payoff. Otherwise, it will be more likely that they will develop worse performing strategies due to misunderstandings of the relationships between what they do and what they get. For example, subjects in an experimental market must understand that drastically increasing production may benefit their performance by increasing their market share, but drops in prices may harm them. Failure to see such relationships can directly hinder the external validity[3] of the experimental market because it would mean that players are not representative of real life, informed decision-makers, who know well what their performance drivers are (Smith, 1982).

Subjects receive feedback about aggregated supply, the resulting price, and their own individual profits

The level of information about the market and the competitors has been shown to have a significant effect on market competition. Increased information about the market (e.g., demand function) often leads to less competition and variability in subjects' actions (Huck et al., 1999). On the other hand, detailed information about competitors (e.g., individual revenues) often leads to increase competition (Huck et al., 2000). Since most firms in real markets do not have access to such detailed information, nor do they have a precise knowledge of market features (e.g., demand function), it is recommended that subjects should be assumed to have aggregate information about both the market and their competitors.

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[3] External validity refers to the extent one can generalize experimental results. That is, to what extent certain experimental results can apply to other individuals in other (similar) contexts.

The experimental instructions use an economic frame
An economic frame means that subjects are set in an economic situation for the experiment (e.g., by the use of economic terms such as firms, or price). Framing is an important issue in many experimental games (for example, see Franciosi et al., 1995, for a study of the Ultimatum Game). Particularly in Cournot markets, it has been found that a neutral frame can make the experiment appear as a computational problem rather than a market situation (Huck et al., 2004). Since this would directly affect the external validity of the experiment, it is important to have an economic frame.

2.2 Field experiments

The extent to which results from a laboratory experiment such as a Cournot market experiment can be extrapolated to a real situation is limited to the extent to which a set of experimental conditions can be generalized and to the extent that it can be argued that such experimental conditions represent a wide range of possible situations in the real system. Such realism is of especially high importance in markets with specific features, in which subjects must have specific knowledge or a specific mind frame.

Field experiments have often been regarded as a methodological way to bridge empirical and experimental research (Harrison and List, 2004). As Harrison and List (2004, pp. 1009–1010) point out: “In search of greater relevance, experimental economists are recruiting subjects in the field rather than in the classroom, using field goods rather than induced valuations, and using field context rather than abstract terminology in instructions.”

Although there does not seem to be a clear boundary between laboratory experiments and field experiments (Chamberlin, 1948; Harrison and List, 2004; Smith, 1962), a number of attempts have been made to define field experiments. In this respect, Harrison and List (2004) have provided a thorough taxonomy of field experiments. This taxonomy postulates that three types of experiments qualify as field experiments: *artefactual field experiments*, *framed field experiments*, and *natural field experiments*. The first type follows the same settings as conventional laboratory experiments, but uses a non-standard subject pool (i.e., the experiments do not use students, but rather a subject pool that is more relevant to the case e.g., traders for financial experiments, or farmers for farming experiments). The second type also depart from conventional laboratory experiment settings, but uses a non-standard subject pool and provides the subjects with a field context in the form of framed instructions as well as available information that resembles a specific field. Lastly, the third type is the same as the second type but is run in an environment in which subjects undertake their tasks as normal, unaware that they are participating in an experiment. The methodological relevance of the field experiments is centered on the idea of some real environments being hard (if not impossible) to replicate in the laboratory. Therefore, it might be better to run an experiment in the actual environment rather than trying forcibly to reproduce the actual environment in the laboratory.

3. Case study: Dynamic decision-making related to budget allocation by Zambian smallholder farmers

Farmers in general and smallholder farmers in particular are repeatedly confronted with budget allocation decisions that include conflicting outcome objectives. For example, short-term production activities such as fertilizer application increase food production and reduce food shortages in the short-term, but compromise future production benefits. By contrast, long-term oriented production activities, such as replenishing depleted soils, trigger sustainable food production in the future, but compromise immediate food availability.

To study how smallholder farmers dynamically decide to allocate a given budget to the two expenditure categories “fertilizer purchase” (representing a short-term production activity) and “soil improvement” (representing a long-term oriented production activity), we ran an experiment in Zambia in south-eastern Africa. The experiment used a Cournot market experiment design and procedure. However, to match the rural and cultural context of Zambia, and to ensure that the farmers could relate to their usual farm context, several adjustments had to be made to the standard protocol and these constituted a crucial basis on which to classify our approach as a field experiment, more specifically as a natural field experiment. However, we do not refer to the field experiment as a field experiment, because our subjects knew they were involved in a data gathering process for research purposes.

3.1 Experimental setting and procedures

We used semi-computerized experiments that each included five subjects (players). As a starting point for the experiments, we adjusted the context-specific simulation model of the Zambian maize market of Gerber (2016) to our experimental setting. The main adjustments included constant population, constant arable land area, splitting the production sector into five farms (each managed by one subject), and making soil improvement decisions endogenous. Figure 1 shows the main feedback processes of the simulation model. A detailed model description is provided in Appendix C of this dissertation.

The simulation model served as a platform where the subjects interacted. It included four main feedback processes. The two expenditure categories “soil improvement expenditure” and “fertilizer expenditure” are part of different feedback loops that both determine yield. Soil improvement slowly increases soil organic matter levels, which in turn has an increasing effect on yield (R1 feedback loop, Figure 1). Fertilizer application increases yields immediately (R2 feedback loop). In both feedback processes, yield affects the next year’s budget through the intermediate variables production, sales and farm income. Thus, these two feedback loops represent the annual farming cycle of Zambian smallholder farmers. The R3 feedback loop represents an important biological aspect of the Zambian plant production system. It adds plant residues to soil organic matter, which is a systemic leverage point for increasing food production in the long run. All the three feedback loops (R1, R2, and R3) represent processes that are specific to each experimental farm. In contrast, the B1 feedback loop represents the aggregated maize market. The sum of all farms' production results in the market supply, which determines the market price and thereby also farm income and the budget for the next growing season. This balancing feedback loop may partly offset benefits that were created through the farm specific R1-3 loops.

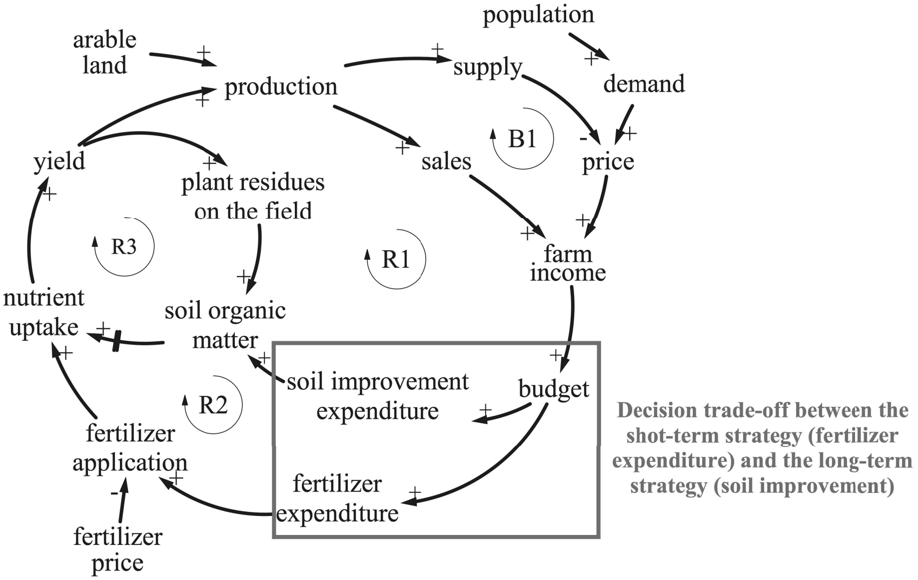

***Figure 1**. Causal loop diagram of the system dynamics model.*

Notes: Arrows indicate causal relationships directed towards the arrowhead. A plus (+) at the arrowhead denotes a positive relationship (where the effect variable changes in the same direction as the cause variable) and a minus (-) denotes a negative causality (where the effect variable changes reversely directed to the cause variable). Feedback loops consist of circular chains of causal relationships and are either reinforcing processes (which self-reinforce the current behavior) or balancing processes (which adjust the behavior towards a goal). R1 – reinforcing soil improvement feedback loop; R2 – reinforcing fertilizer feedback loop; R3 – reinforcing soil organic matter feedback loop; B1: balancing supply feedback loop.

Source: Gerber et al. (2017).

The experiment was set to last nine rounds. In each round, decisions were collected and applied for four years in the simulation model. This allowed experiments to be conducted within a feasible amount of time (ca. 90 minutes per experiment) and still covered a 35-year period, which was long enough for long-term processes such as soil dynamics to unfold. As performance indicator we used the subject's accumulated production over the total experiment duration.

We instructed the subjects verbally in their local language, following a standardized protocol (Appendix A). Important parameters to acquaint the subjects with their "experimental farm" (e.g., farm size and costs associated with the decisions) were part of the protocol and were therefore common knowledge, including symmetry across firms. The subjects were incentivized by presenting five standardized, physical rewards (2 kg sugar, 1 kg sugar, 750 ml cooking oil, big bar of laundry soap, and small bar of laundry soap) prior to the experiment. The subjects were told that performance was measured in accumulated maize production and that the best performing farm could choose a reward first, then the second, and so forth until only one reward remained for the last subject. To avoid communication, the subjects were spatially separated during the experiment. In each round of the experiment – prior to the subjects' decision – we provided the following information to each subject: the subject's budget, its yield, its production, and the market price. Based on this information, the subjects decided on how to allocate the budget to the two expenditure categories "soil improvement expenditure" and "fertilizer expenditure". In the absence of a computer network, the information was transmitted both, verbally and written (on a standardized record sheet, Appendix B). The subject's decisions were collected and entered to a central computer. After simulating four years, the current budget, yield, production and market price was noted on the record sheet and communicated to the subjects as a base for the next decision.

After completion of the nine rounds we calculated the accumulated maize production for each subject and rewards were chosen according to the rank. The experiments ended with a debriefing session where subjects expressed and exchanged their experiences, thoughts and decision rules.

The experiments were conducted in August 2016 around Mumbwa in Zambia. The subjects were recruited from smallholder farm communities and were either couples or widows that actually run and decide on a real farm in their everyday life. No subject participated in more than one experiment. The experiments were facilitated by local field assistants who spoke Tonga (the local language), and who were specifically trained. In total we conducted 15 experiments with 75 subjects, of whom 50 were couples and the remaining 25 were singles.

3.2 Deviations from common Cournot experiments

The experimental setting and procedures included some deviations from the standard protocol, which is normally applied in common Cournot experiments. In the following we highlight those deviations. We start with the two structural adjustments of our model to the standard protocol for Cournot market experiments (high degree of model complexity and lack of complete structural transparency; dynamic endowment).

High degree of model complexity and lack of complete structural transparency
Providing information about the market's mathematical representation to the subjects (i.e., providing structural transparency) gives the subjects a good understanding of their setting. Structural transparency can – in specific cases – also be an important prerequisite for arguments about the subjects' rationality. However, to qualify our approach as a field experiment, we omitted to provide structural transparency. To increase the external validity of our potential findings about smallholder farmers' decision-making, we framed the experiment so that it would be as close to a natural field experiment as possible. This implied that the subjects' decision environment needed to be as close to their normal decision environment as possible. Thus, our model structure is distinctly larger and richer in technical details than model structures in other Cournot market experiments. Consequentially, and because of the expectedly high variations in the education levels among the subjects, we did not provide full structural transparency to the subjects. Moreover, structural transparency

about the farm and agricultural markets is normally not available for Zambian smallholder farmers.

Dynamic endowment

Allocation decisions in Cournot market experiments are typically based on a constant budget. However, this is not the case in Zambian farmer's reality, in which budgets change over time. Thus, to ensure that the Zambian smallholder farmers' reality was reproduced as closely as possible, we applied a dynamic endowment (i.e., a budget that changes over time), based on the dynamic interactions of the subjects on the market.

Semi-computerized setting

To ensure the comparability of experimental data, Cournot experiments are often conducted under fully computerized settings where all subjects receive the same information. The Zambian smallholder farmers' low levels of familiarity with computers, their varying degrees of literacy, and outdoor experiments in rural villages all meant that a fully computerized setting with written instructions was not possible. Instead, we used a semi-computerized setting and tried to ensure that all subjects received the same information by using specific procedures; i.e., verbal instructions following a standardized protocol (Appendix A), spatial separation of the subjects during the experiment, and standardized communication during the experiment by using a record sheet (Appendix B) and verbal explanations. Trained field assistants facilitated the data gathering process.

Tangible rewards

Monetary rewards are often used in Cournot experiments to incentivize subjects, because money offers "monotonicity" (Smith, 1982). Nevertheless, we used tangible rewards instead of monetary rewards because a "game" with monetary rewards would very likely have been interpreted as gambling, for which we would have needed a concession. Additionally, a "gambling approach" would probably have distracted the subjects' focus from their farm mind-set, which was crucial for a natural field experiment. The tangible goods consisted of household items that smallholder farmers needed in everyday life (2 kg sugar, 1 kg sugar, 750 ml cooking oil, big bar of laundry soap and small bar of laundry soap).

Payoff function

Zambian smallholder farmers maximize production rather than profits (Umar, 2014). Thus, we used total (accumulated) maize production of each subject as a performance criterion instead of profits. The rewards were chosen according to each farmer's rank within the group. Thus, the best performing subject could choose a reward first, then the second, until only one reward remained for the least-well performing subject.

No market supply information

We did not provide information about aggregated market supply to the subjects because such information would normally not be available for Zambian smallholder farmers.

Debriefing session

After the data gathering process, we brought the subjects together for an assisted debriefing session, during which they revealed the reasoning behind their decisions and shared their thoughts.

4. Results and Discussion

In this section, we provide and discuss evidence from two main perspectives. The first perspective focuses on the outcome of our experiments. Thus, we briefly present the quantitative data that we gathered, the analysis that we conducted and the insights that we gained. The second perspective focuses on the experimental settings and procedures. Through the interaction with the subjects during and after the experiments we collected empirical, qualitative information about the experimental setting and procedures. We present and discuss this qualitative information, before we end this section with reporting an unintended but positive side effect of our experimental approach.

4.1 Outcomes: data, analysis, and insights

Decision data

The semi-computerized setting with a simulation model allowed to easily storing the quantitative data of allocation decisions and their impact on model variables. Figure 2 displays the trajectories of key variables for all subjects and markets. The subjects decided periodically on the allocation of a given budget to fertilizer expenditure and soil improvement expenditure, which determined production (R1 and R2 loop, Figure 1). Production in turn determined the budget for the next growing season directly and indirectly (through price, B1 loop). The model was calibrated such that maize production showed an increasing trend, which reflects the reality on many Zambian farms over the past two decades. The increasing production lead to decreasing prices, which in combination with production, determined the budget.

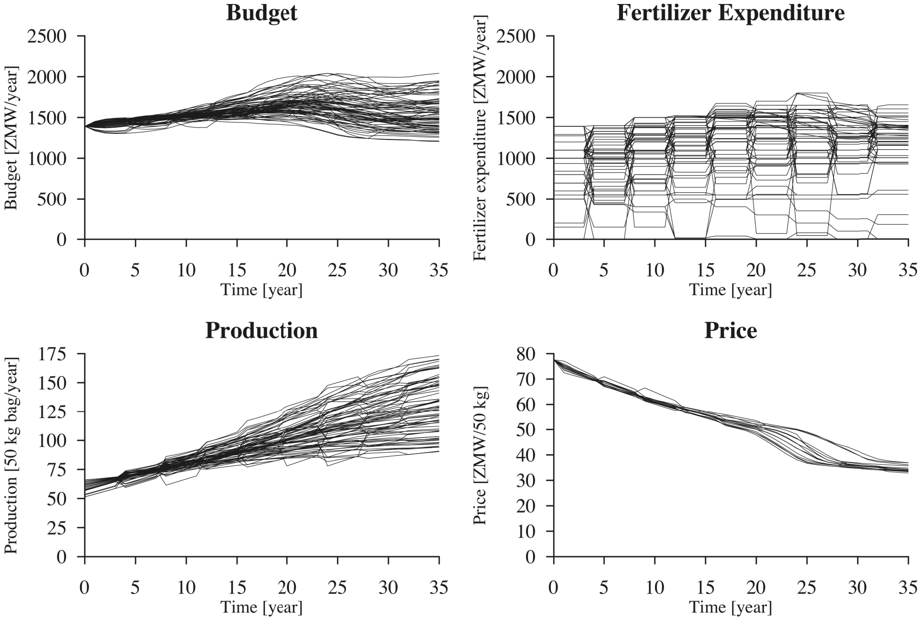

Figure 2. *Trajectories of key variables obtained through the experiments.*

Analysis of the data

We analysed the data in several ways. First, we tested whether the subjects had a bias in their decisions towards one of the expenditure categories (fertilizer and soil improvement). To test for such biases we applied Mann Whitney tests to the values of fertilizer expenditure of each subject and market. Second, we were interested in detecting different decision strategies and how they affected performance (production). Thus, we applied a hierarchical cluster analysis using squared Euclidean distance as a clustering criterion in order to group the decision trajectories based on fertilizer expenditure. Then we linked the obtained clusters to performance indicators. Third, we wanted to understand how subjects that applied a certain decision strategy formed their decisions. Therefore, we ran linear regressions for each subject to identify the subject's heuristic (fertilizer expenditure was the dependent variable and the provided information cues – yield, production, budget, and price – were the independent variables). Based on the subject-specific heuristics we calculated the decision strategy's heuristic by averaging the regression coefficient of the subjects within each cluster (each cluster represented a decision strategy). Fourth, we implemented the heuristics, i.e., the mathematical decision rules, in the simulation model (Figure 1) and tested the performance implications of the heuristics by means of simulation. A detailed description of the analysis and results is presented in Gerber et al. (2017). In the following we highlight some key findings that illustrate that our experimental approach lead to valuable insights.

Bias towards fertilizer use

Overall, our results suggest a significant bias toward fertilizer expenditure. This outcome is consistent with findings published earlier in the literature, in which it is suggested that farmers favor strategies that give them higher short-term profitability, even at the expense of better future results (Donovan and Casey, 1998). This short-term mind-set provides an explanatory hypothesis for why long-term policies, such as conservation agriculture, do not have a high success rate in terms of scaling-up (Giller et al., 2009).

Variation in decision strategies

Besides the above-mentioned overall bias towards fertilizer expenditure, a substantial number of the subjects were not biased towards fertilizer expenditure. This finding shows that although fertilizer expenditure is the most common strategy, many farmers may be willing to prioritize soil improvement over fertilizer application or to implement a combination of both.

Decision dynamics and success factors

The results of the regression analyses showed that most of the subjects in our experiment made their decisions without taking into account the information provided to them. This finding suggests that most of the participants used pre-existing decision rules without any dynamic adjustments. A minority of the participants showed dynamic adjustment to their decisions: they changed their decisions depending on the context. We found that the initial ratio of fertilizer expenditure to soil improvement expenditure was crucial in determining how successful a given decision strategy was in terms of production, both in the case of dynamic adjustment and non-dynamic adjustment.

Practical implications

Our findings revealed that a mind shift from short-term production activities towards long-term production activities is required to enhance food production sustainably and increase the natural resource base in the long run. However, the question of how to achieve such a mind shift in Zambian smallholder farmers is not trivial. The variation in their decision strategies implies that there is no single solution that fits all farms, but that agricultural extension (i.e., consultancy for farmers) should focus on capacity building and the farmers' ability to adjust adequately to changing framework conditions. Since long-term production activities provide outcomes only after a number of years, it is crucial to find means to compensate for short-term production losses.

4.2 Discussion of experimental settings and procedures

In this section, we discuss the ways in which our experiment differs from the standard protocol for Cournot experiments. Also, we discuss why such deviations were needed, and how they contributed to the value of our approach. This provides the basis for reflecting on the possibilities to abstract from our case study to other, related dynamic decision-making issues in commodity markets in the conclusions section.

High degree of model complexity and lack of structural transparency

Our experiment used a context-specific model calibrated on empirical data. For this reason, the number of variables and parameters were distinctively higher than those in the economic models commonly used for Cournot experiments. This higher complexity, coupled with procedural limitations such as varying degrees of literacy and low familiarity with computers among the subjects, meant that we did not provide full structural transparency. The field assistants who interacted directly with the farmers during the experiment reported that the farmers were well able to familiarize themselves with the provided setting and were highly engaged in the decision-making. Also, the farmers' statements in the debriefing session revealed that they could relate their experiences of the experimental setup to their real-life farms. Thus, at the cost of not being able to theorize on economic equilibriums[4], the high model complexity and the resulting lack of structural transparency was a setting that allowed the farmers to relate their experience of their experimental farms to their real-life farms.

Dynamic endowment

The dynamic endowment in our experimental design means that comparison of our results with previous works would be difficult. Moreover, dynamic endowment creates a high degree of autocorrelation in subjects' performance: subjects' current

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[4] Market supply and demand curves have been traditionally thought to be in constant process of reaching a balance. An economic equilibrium is a point in which such balance is achieved. Well-known economic equilibriums include the Nash equilibrium, the joint maximization equilibrium and the perfect competition equilibrium.

performances will be heavily determined by their previous performances. This could lead to serious divergences across farmers' performances due to path dependence (Yesuf and Bluffstone, 2009). However, the inclusion of a dynamic endowment allowed us to explore how farmers made their decisions in light of realistic conditions, such as the possibility of falling into the poverty trap (Pugliese et al., 2017). The poverty trap is the incapability of farmers to escape poverty, once they fallen below a certain poverty threshold. Our dynamic endowment reflects this effect, and it made the economic setup more realistic for our study of Zambian farmers.

Semi-computerized setting

Unlike most Cournot experiments, our experimental design was not fully computerized. Given the subjects' varying degrees of literacy and low familiarity with computers, a fully computerized experiment (in which farmers would have interacted directly with the computer) was practically impossible. Under the given conditions, a fully computerized setting would only have been possible if we had used facilitators for communicating information and interacting with the computer. However, this would not have provided additional value to our setting. Moreover, an unfamiliar object such as a computer would most likely have distracted farmers' mind-sets during the decision process, which is a crucial component in field experiments as described by Harrison and List (2004). The verbal communication of the experiment instructions, as well as the standardized oral and written interaction between the farmers and field assistants ensured that the farmers understood the provided information, even though some subjects were illiterate.

While a fully computerized setting would have ensured that all subjects received the same information, we minimized information biases by specifically training the field assistants to ensure that all subjects received the same information. The geographical separation of subjects during the experiment effectively avoided communication among them, which is an important prerequisite to avoid collusive behavior. Thus, our semi-computerized setting meant that, in the given context, our experimental design was as close as possible to the standard conditions stipulated by Huck et al. (2004).

Payoff function

While the original Cournot oligopoly model solutions are based on the maximization of profits (given a certain production level and a resulting price), our experiment used only production as a basis for the payoff function. Consequently, maximization of production excludes any possibility of having an economic equilibrium in its pure sense and farmers will produce as much as possible even if that implies lower prices for them. While lower prices can reduce farmers' future endowments, higher production levels can compensate for them if the increase in production outweighs the price decrease. Thus, shifting the focus from profits to production may have implications for the farmers' decisions. However, having profits as a basis for payoff function in the Zambian case is unrealistic. Zambian farmers are food insecure, which means that in their daily activities their primary focus is on producing as much food as they can, instead of making as much profit as they can (Umar, 2014). Our experiment was therefore designed to be consistent with this focus, by treating accumulated production, not profit, as a basis for farmers' payoffs.

Tangible rewards

Subjects were paid with tangible items to avoid misinterpretations, since in the local context monetary payments could have been mistakenly associated with gambling, which might have distracted the farmers' mind set and had an adverse effect on any future research projects with the farmers. While tangible rewards have been shown to be at least as good as monetary rewards to incentivize performance (Kelly et al., 2015), this reward design poses the challenge of "monotonicity" (Smith, 1982). Monotonicity refers to the property of a good of always being equally good in incremental terms. As an example, most people are likely to agree that having USD 200 is better than having USD 100, and, in more or less the same way, having USD 300 is better than having USD 200. While we cannot guarantee monotonicity in any of the goods we used to reward subjects' performance, we mitigated the lack of it by assigning an order to choose the items instead of defining one specific item as the first prize, another item as the second prize, and so on. In other words, by giving the subject with the best performance the chance to choose among a set of items first, we expect that he or she would choose the item with the highest utility value to him or her. Although the order does not guarantee monotonicity across subjects' utilities, it certainly makes sure that the subjects with the best performance gained more value from their choices, since they had more items to choose from, compared with the farmers who performed least well. From subjects' comments made during the introduction to the experiment and the reward ceremony, it became clear that the setting with a production-based payoff function and tangible rewards motivated the subjects to perform as well as possible. Farmers saw each other when they were called to collect their prizes, which elicited another intangible reward: acknowledgement. It has been shown that acknowledgment is a powerful reward in certain communities, especially in communities in which all members know each other (Bradler et al., 2016). Since this is the case for farming communities, acknowledgment of the farmers with the best performances should reinforce the value of the tangible reward, such as the rewards received during the reward ceremony. Our results from the debriefing session also suggest there is an extra motivation for farmers, namely to learn. The Zambia smallholder farmers wanted to do their best in order to learn as much as they could from the experiment. Thus, the combination of rewards, acknowledgment and interest in learning are arguments in favor of the validity of our approach.

No aggregate market supply information

Our experimental design does not present aggregate market information to subjects. This can have implications for the level of competition between the subjects (Huck et al. 1999). However, it is not realistic to assume that Zambian farmers have a comprehensive understanding of the market. Furthermore, giving an additional variable to the farmers for consideration would have made our design more complex, especially when such variables do not represent a piece of information they are used to dealing with in their daily activities. In other words, not having information would be more realistic than having it. Furthermore, dealing with a piece of information they are not use to dealing with, may alter subjects' decision processes, and in our case this could have affected the external validity of our results, and thus defeating the purpose of our experiment. For these reasons, we refrained from giving the subjects information about the aggregate market supply, even though this might have implied changes in competition levels across farmers, as indicated in Section 2 above (Huck et al. 2000).

4.3 Implications from qualitative information by the subjects

During the debriefing session after the experiment, besides qualitative information about their decision rules and strategies, the subjects repeatedly expressed one positive, albeit unintended side effect of the experiment. Despite the unambiguous statement in the introduction to the experiment that we were gathering information for research purposes, the subjects expressed that they themselves learned a lot from the experiment. It seemed that some of the subjects had forgotten that they were part of a data collection process and thought that they had joined a capacity-building event[5]. Common learning outcomes stated by the subjects included the following: the importance of planning and making decisions as a couple (apparently, on many farms, the couples did not decide jointly in real life); the relevance of allocation decisions for production outcomes; the importance of dynamic book keeping; differentiating between short-term and long-term production activities and knowing their impacts; and differentiating between the concepts of yield and production. Thus, our experimental approach might not only serve as a method to collect decision data but also constitute a viable means for interactive capacity building.

5. Conclusions

Cournot market experiments propose a useful frame to analyze production related decision-making and how such decisions affect the performance of competing firms. However, common Cournot market experiments are based on a series of fairly strict assumptions (standard conditions). In reality, there are circumstances that do not coincide with all the assumptions in Cournot experiments. For example, non-standard markets (i.e., markets where participants have uncommon objective functions, such as

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[5] A capacity-building event in this context is a training session for farmers.

maximizing production instead of profits) and procedural limitations (e.g., due to lack of available infrastructure, or participants' educational and cultural background) pose challenges to run Cournot market experiments. Nevertheless, there is vital research interest to also study decision-making under such circumstances. In this article we reported a case study about budget allocation decisions of Zambian smallholder farmers, which included both, a non-standard market setting and procedural limitations. To study the farmer's decision-making we used Cournot market principles as a basis for our experimental design and complemented it with principles from field experiments. Based on our case study we gained several key insights that exceed the specific case of Zambian farmers and that we believe are of general interest to researchers who want to study dynamic decision-making based on experiments.

5.1 Scientific value of non-standard Cournot experiments

Standard conditions provide a reliable framework with which to control important variables in Cournot markets, such as the levels of competition, cooperation, subject engagement, and salience (Huck et al, 2004). To be clear, standard conditions are not thought of as a boundary, beyond which experiments cannot be valid or valuable for different purposes. For example, standard conditions can serve as a benchmark to infer where different behaviors may arise from (e.g., a higher level of competition may be rooted in the level of information given to the subjects, instead of the actual context in which an experiment is framed). However, experiments with severe deviations from the standard conditions generate results that may be difficult to compare with other Cournot market studies that use standard conditions as a benchmark. Although standard conditions must be considered in order to study the theoretical properties of the Cournot market formulation, we found that relevant scientific knowledge, such as information about dynamic decision-making, can arise from non-standard experiments and therefore, non-standard Cournot experiments are worth considering. In particular, our experimental design and procedures allowed subjects to familiarize themselves with their experimental firm, which is a key issue when conducting field experiments with real decision makers. Furthermore, the analysis of the experimental data revealed important information about how Zambian smallholder farmers make budget allocation decisions with conflicting long- and short-term production objectives. Such trade-offs occur in several situations where production decisions not only have economic consequences in the short-term but also wider sustainability impacts in the long-term. These trade-off situations are crucial to study, even if they do not represent a standard Cournot market. Thus, we propose that standard conditions should be viewed as resources rather than limitations.

5.2 Initial guidelines for non-standard Cournot model applications

Using the standard conditions as resources is not trivial and giving a clear-cut generalized framework for adapting Cournot standard conditions to all problems is not entirely feasible. However, based on our case study, we suggest the following initial guidelines for non-standard Cournot model applications.

First, one needs to be clear about a study’s objective. Applying severe deviations from the Cournot standard conditions may imply that it is impossible to contribute to the theoretical economic literature, for example, about economic equilibriums. However, if one wants to investigate decisions of real decision makers (i.e., to conduct field experiments), the deviation from Cournot standard conditions may be necessary. Thus, depending on the study’s main objective, severe deviations form standard conditions are either essential or undesirable.

Second, one must think of how well the standard conditions represent the characteristics of the market of interest. There is a solid body of literature that analyses what deviations from each standard condition may entail (e.g., Huck et al., 2000; Huck et al., 2004). This literature can give useful indications for possible biases and compound effects that may arise when one deviates from standard conditions. Depending on a study’s objectives and taking into account this literature, one can judge what deviations may be feasible. For example, a shift from fixed budgets to dynamic endowments – as in our case – is most likely adequate for a wide range of commodity markets where market participants face severe budget constraints so that the economic consequences of their decisions (at a specific point in time) directly affect their economic endowment in the subsequent decision intervals. Thus, it is important to know in which regards the market at hand is different from the standard conditions.

Third, one must think about what is meaningful for the subjects by taking into account their context. The subjects may attribute specific values to specific variables. For example, in our case, given the food insecurity faced by farmers, it made sense to shift the focus from profits to production as an objective function. In a similar way it was adequate to conduct semi-computerized experiments because fully computerized experiments would most likely have detracted the farmers from the farm setting, which was a key issue to qualify our study as a field experiment. Thus, such special conditions may require deviations from standard conditions and procedures, such as shifting the focus from profits to other variables (e.g., market share or price), or from a fully computerized setting to a semi-computerized setting.

The guidelines above are based on one case study of Zambian smallholder farmers. Many of the modifications that we performed were context-specific (i.e., they related to the case of Zambian smallholder farmers), and therefore cannot be extrapolated to all cases. This means that more research is needed to further specify and consolidate these initial guidelines. Additional case studies in different contexts can reveal other critical points. And semi-structured, post-experiment interviews could be a means to systematically collect standardized data.

5.3 Potential as a learning methodology for interactive capacity building

Despite the fact that farmers in our case study had been told they were going to participate in an experiment, many of them later stressed how much they had learned from the experiment. The most interesting aspects they mentioned were: the importance of joint decision-making (i.e., making decisions as couples); the relationship between their budget allocation decisions and their resulting production; the importance of keeping track of their decisions; the realization of existing biases; and learning to differentiate between agricultural concepts. Their positive feedback indicates the potential of using non-standard Cournot market games as a vehicle for simulation-based learning (Andersen et al, 1990; Davidsen and Spector, 1997; Senge, 1994; Sterman, 1992). Further research is needed to explore this potential in depth.

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Appendixes

Appendix A: Data Gathering Protocol

1. Gather the participants (5 couples, that in real life each actually run a farm together).

2. Introduction and Instructions: Hello and welcome everybody.

Introduction of all that are present

A. Purpose

Thank you for being here. Today we gather information for learning how you make different decisions. Andreas is doing a schoolwork study for his PhD in collaboration with Dr. Nyanga at UNZA[6]. He is interested in learning how you make decisions as couples. The information will be used for academic purposes and may be published in academic journals. Is that clear and ok for you?

B. Roles

We would like to gather the information through playing a game together. The roles are: I am the moderator, who will interact with you. Andreas is the computer man, who will be putting the information in the computer and giving the results. Cain and Eukeria will help me moderating the process, transmitting information between you and the computer man. You, the couples, are the players who make decisions.

C. Game

Every couple will manage a farm. You all have a common main goal for your farm. In this game the main goal is to maximize your accumulated maize production over the whole game. To reach the goal of maximize your production, you must decide how much money (Kwachas) you want to spend on two options. The first option is buying <u>own</u> fertilizer (not through government or NGO subsidies). And the second option is spending financial means to improve your soil through crop residue retention and manure application. In this game we just have these two options and we

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[6] University of Zambia

are not considering other options such as lime application, crop rotation, Musangu tree plantation, etc.

Here is some information to understand your farm: Each couple cultivates 8 limas (equivalent to 2 hectares) of maize on its farm, so your decisions are limited to this area. The maize yield level is currently around 7 bags of 50kg per lima; the current/starting production therefore is around 60 bags of 50kg per farming season. The current/starting producer price of maize at your market is around 75 Kwacha per 50kg bag.

In the beginning your budget for the two options is 1392 Kwacha. In the first option, which is buying fertilizer, a 50 kg bag of fertilizer cost 550 Kwacha. In the second option, which is crop residue retention and manure application, a lima costs you 117 Kwacha, adding external organic matter becomes more expensive.

For you to make decisions, the moderator will come to you and give you information about your budget, yield, current production and market price. You will then decide how much of the budget you want to spend on fertilizer and how much you want to spend to improve your soils. The moderator will take note of your decision and bring it to Andreas. He will put your decision into the computer and calculate the new budget, yield, production and price. The moderator will bring this new information back to you so that you can again decide how much money you will spend for fertilizers and soil improvement. We will have 9 rounds in this game. Thus, these dynamics will continue until we complete 9 periods (you make 9 decisions). The game will be completed in 1-2 hours approximately.

At the end of the game, the computer calculates your total production for the entire game and you will be rewarded with a present depending on your results. We brought a couple of items of which the best performing couple can choose one item first, the second best performing couple second, etc.

Show the goods (2kg sugar, 1kg sugar, 750ml oil, big laundry soap, small laundry soap)

If you have difficulties to make your decision, think of how you decide on your own, real farm and always keep in mind that your goal is to maximize your production!

We will have the possibility to clarify procedural questions during the game, but not ask for help in decision making. So far, is the game clear to you? Are you willing to participate? If you do not want to participate or feel uncomfortable, you can withdraw.

Remarks to the instructor:

It is ok to clarify procedural questions: e.g., what happens after we make a decision? Do we have to spend the entire budget to these two policies? Etc.
It is also ok to clarify the meaning of words (e.g., yield)
Do not give clues that may directly influence the decision making process. E.g., do not answer questions regarding what should be done such as "should I allocate more on fertilizers?" or "How can I make the highest production in the game?"

3. Split the participants up.

In this game it is the idea that you keep your decisions and results as a secret within your farm and do not share them with the other couples. So please, keep communication between the farms at a low level. However, once the game is finished and we have all the results from everyone, you are very free to share experiences and strategies with each other!
Give your best and good luck!!

4. Start the actual rounds.

After first round: explain that yield, production, price and budget changes. Costs stay the same.

5. Save the rounds.

Take a copy (soft or hard) from the interaction sheets and save it.
Give a hard copy to the farmers as a feedback.

6. Conclude with an aftermath session.

At this point the game is over and you are free to leave if you wish. However, if you appreciate, we will have a feedback session explaining some ideas of the game.

Appendix B: Record Sheet

Farm Number:________
Name of Participants:
____
____

Data Collection Set-Nr:___

Input prices:
- 50 kg Fertilizer costs 550 ZMW
- 1 lima improved soil costs 117 ZMW, for further improvement the price increases

Round 0	Yield ≈7 bags/lima	Production ≈60 bags	Price ≈75 ZMK/bag	Budget 1392 ZMW	Soil	**Fertilizer**
1	Price	Yield	Production	Budget	**Soil**	Fertilizer
2	Production	Price	Yield	Budget	Soil	**Fertilizer**
3	Yield	Production	Price	Budget	**Soil**	Fertilizer
4	Price	Yield	Production	Budget	Soil	**Fertilizer**
5	Production	Price	Yield	Budget	**Soil**	Fertilizer
6	Yield	Production	Price	Budget	Soil	**Fertilizer**
7	Price	Yield	Production	Budget	**Soil**	Fertilizer
8	Production	Price	Yield	Budget	Soil	**Fertilizer**
9	Yield	Production	Price	Budget	**Total Production**	

Date: ______________ Place: ______________

Article 4

How do Zambian smallholder farmers allocate their budget? Evidence of dynamic decision-making based on a Cournot field experiment

How do Zambian smallholder farmers allocate their budget? Evidence of dynamic decision-making based on a Cournot field experiment

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Abstract

Smallholder farmers in sub-Saharan Africa repeatedly face situations of complex and dynamic decision trade-offs, which include allocating money across short-term and long-term production activities. Short-term activities such as fertilizer application help to cover immediate food needs, but compromise future food production. Long-term production activities, such as building up soil fertility, are important systemic leverage points for future food production, but compromise present-day harvests. This article reports a Cournot field experiment conducted with Zambian farmers to investigate farm management decision-making in a dynamic context with conflicting production objectives. The results revealed that most Zambian smallholder farmers were biased towards short-term production activities, which led to suboptimal performance in production. Despite this bias, the farmers applied various distinct dynamic and non-dynamic decision strategies, with varying production outcomes. Simulation experiments with the decision strategies revealed that most decision strategies resulted in rather stable production patterns. However, following some decision strategies, the production patterns strongly varied when the strategies interacted with other strategies in the same market and the produce was therefore subject to the strategies' endogenous interactions within the market. Given the farmers' strong preference for fertilizer, the findings suggest that a shift towards favoring long-term oriented production activities is required to increase food production sustainably in sub-Saharan Africa. In conclusion, the various decision strategies and their endogenous interactions reinforce the need for building adaptive capacity among smallholder farmers in order to apply context-specific decision strategies.

Keywords: Farmers' decision-making, Zambia, maize production, non-cooperative Cournot market experiment, system dynamics

1. Introduction

Smallholder farmers in sub-Saharan Africa repeatedly face situations of complex and dynamic allocation trade-offs. Should a farmer allocate his or her budget to farm activities that immediately increase food production and compromise sustainable long-term production? Alternatively, should the farmer allocate his or her budget to farm activities that increase food production in the future and tolerate smaller harvests today? The answers to these questions are not trivial, for three reasons. First, the level of food availability is low in sub-Saharan Africa (GFSI, undated) and the immediate need for food may force farmers to focus on short-term production objectives (e.g., through fertilizer purchases). Second, food production systems "memorize" farm decisions through their resources stocks (e.g., soil organic matter), which are an important source of long-term sustainability and resilience (Stave and Kopainsky, 2015). Third, the complexity of the trade-off arises from the dynamic and interlinked nature of farm decisions: whereas budget allocation decisions are restricted to individual farms, the decision outcomes, such as total production, are not restricted in the same way. The aggregated production of individual farms affects the market price, which in turn has an effect on the farm budget for the next growing season and subsequent decisions. Thus, the dynamic nature of such allocation trade-offs and the dynamic environment of the food production system in Zambia mean that allocation decisions are complex. Additionally, the severity of the decision-making is indicated in the conflicting benefits of short-term and long-term decision alternatives.

Understanding how farmers decide dynamically (i.e., over time) is of central importance to policymakers, agricultural extension officers and food system scholars because farm decisions greatly affect food system outcomes, such as food availability. Low levels of food availability are an enduring challenge in sub-Saharan Africa and even the farmers themselves, who produce the food, are affected by food shortages. The disparity between the continuously growing demand for food on the one side and lagging production on the other side not only results in low food availability, but also depletes the natural resources used in sub-Saharan Africa's food systems (Godfray et al., 2010). Low levels of soil nutrients and soil organic matter, unsustainable water usage, and biodiversity losses all threaten the long-term ability to provide ecosystem services (Foley *et al.*, 2011). Additionally, climate change is likely to cause production losses and yield variability in important crops, such as maize (Lobell *et al.*, 2008). This context highlights the urgent need for approaches that enhance sustainable food production.

The literature on sustainable food production approaches is vast and strategic lines of action that include increasing resource efficiency and closing yield gaps have been summarized; e.g., by Foley *et al.* (2011). Within these strategic lines of action, soil fertility and soil organic matter (SOM) play central roles because they affect agricultural productivity in general and resource efficiency in particular (Kumwenda *et al.*, 1997). Currently, SOM levels are low in sub-Saharan Africa and thus contribute to the big yield gaps. Research has shown that SOM is a systemic leverage point to enhance food production sustainably, and that high levels of stocks such as SOM have the potential to buffer external shocks (Gerber, 2016; Stave and Kopainsky, 2015). However, to increase SOM levels is a long-term process that requires consecutive investments. Since many farmers have short survival-oriented time horizons, Donovan and Casey (1998, p. 25) argue that smallholder farmers "have very high discount rates for future benefits that are far in the future." Consequently, in order to increase short-term food availability, the main focus of public agricultural policies in many countries in sub-Saharan Africa is to increase the use of inorganic fertilizers through fertilizer subsidy programs (FSPs) (Banful, 2011; Jayne and Rashid, 2013). Whereas fertilizer use in general and FSPs in particular lead to higher levels of food production in the short-term, the application of fertilizers fails to increase SOM stock levels effectively in the long-rung and therefore fails to enhance an important systemic leverage point (Gerber, 2016; Morris *et al.*, 2007). In acknowledging this limitation, governments' and private organizations' policies have focused on conservation agriculture that aims to build up SOM levels. However, despite considerable implementation efforts and the plausible potentials, conservation agriculture has never played a dominant role to the extent that it could have become a real alternative to FSPs (Giller *et al.*, 2009). This reinforces the need for long-term strategies and the need for a better understanding of farmers' decision-making in a dynamic context in order to inform policymakers and agricultural extension officers.

Despite the relevance of understanding farmer' decision-making in a dynamic context, little research has been conducted on sub-Saharan Africa's smallholder farmers' decisions in general and their decisions about recurrent allocation trade-offs in particular (Saldarriaga *et al.*, 2014). Zambia is an exemplary case where food availability is chronically low (GFSI, undated). Many technical, political and social aspects of the Zambian food system have been intensively researched with the aim of increasing food availability: farming practices such as conservation agriculture (e.g., Nyanga, 2012; Umar, 2012), policy interventions such as FSPs (e.g., Jayne and Rashid, 2013; Mason *et al.*, 2013), and health issues that affect food systems such as HIV/AIDS (e.g., Chapoto and Jayne, 2008; Chapoto *et al.*, 2011). However, the literature on farmers' decision-making is restricted to a few topics, such as the adoption of technology (Grabowski *et al.*, 2016; Langyintuo and Mungoma, 2008; Umar, 2014), identification of household decision-makers (Kalinda *et al.*, 2000), production decisions in response to public market interventions (Mason and Jayne, 2013; Mason *et al.*, 2015; Xu *et al.*, 2009), normative decision modeling (Holden, 1993; Katongo, 1986), and static farm expenditure decisions (CSO, 2015). Thus, the dynamic nature of farm budget allocation to production activities in Zambia and elsewhere in sub-Saharan Africa has largely been overlooked in the literature published to date. This is especially true in cases where farmers face trade-offs between short-term and long-term production objectives. To our knowledge, no study has investigated such budget allocation trade-offs in a dynamic context.

This article contributes to filling the gap in the literature by reporting the application of a dynamic, non-cooperative Cournot oligopoly experiment to the case of smallholder farms in Zambia. In the experiment, the participants (subjects) iteratively decided on how to allocate a given, dynamic budget between two maize production activities: fertilizer purchases (a strategy to enhance maize production the short-term) and the addition of organic matter to the soil (a strategy to enhance maize production in the long run). Unlike other Cournot studies that have mainly contributed to the decision literature on a purely theoretical level, we applied a Cournot experiment to generate empirical evidence about decision-making based on a field experiment with real decision-makers (see Lara-Arango *et al.*, 2017 for conceptual details). A Cournot experiment frame allows decision data to be collected in a dynamic, interactive context. We contribute to existing literature and policy debates in several ways. First, by adapting the standard protocol developed by Huck *et al.* (2004) to the Zambian field setting (i.e., in the absence of a computer network). Second, we corroborated previous assumptions that farmers' decisions are biased towards a short-term strategy (fertilizer use) rather than a long-term strategy (soil improvement). Third, formalized decision heuristics revealed that some farmers decide dynamically based on farm and market information, while others decide on non-dynamic, a priori heuristics. Finally, we tested the heuristics in a dynamic simulation model and found that the performance of some heuristics depended to a large extent on the endogenous interactions with other strategies that are present in the market. Our findings are relevant to decision makers and practitioners as a basis for sustainable policy formulation.

The article is structured as follows. In the next section, were describe the experimental design and procedures. Thereafter, we present the results of the experiments, identify strategies and their heuristics, and analyze the dynamic implications of the heuristics in terms of performance. Finally, we discuss our findings and draw conclusions based on the results and analyses.

2. Experimental design and procedures

2.1 Experimental design and setup

We used a semi-computerized experiment based on a Cournot market with non-standard conditions. The setup included five subjects (players), who were not permitted to communicate with one another, in order to avoid collusion. Although our experiment was designed on the basis of a traditional Cournot market, our main interest was to study decision-making by real farmers in an exploratory field experiment (Harrison and List, 2004). Thus, to ensure that the subjects associated the experiment with the situation on their farms, our experiment differed from Huck et al.'s (2004)[1] standard conditions on two structural points (for a detailed discussion of the adjustments to the standard protocol, see Lara-Arango *et al.*, 2017). First, we used a model that was distinctly larger and richer in technical details than other Cournot market experiments (e.g., Arango *et al.*, 2013), in order to make the setting as realistic as possible. Second, we considered a dynamic farm endowment, in which the current budget was determined by the market price and the subject's sales in the previous round, as was the case on real farms.

As a starting point, we used a context-specific, economic system dynamics model of the Zambian maize market—the maize market model, including its theoretical and empirical foundation, which has been described in detail earlier by the first author of the present article (Gerber, 2016)—which we adjusted to the experimental setup. The main adjustments included constant population, constant arable land area, splitting

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[1] Standard conditions: a. Interaction takes place in fixed groups; b. Interaction is repeated over a fixed number of periods; c. Products are perfect substitutes; d. Costs are symmetric; e. There is no communication between players; f. Participants have complete information about their own payoff functions; g. Participants receive feedback about aggregated supply, the resulting price, and their own individual profits; h. The experimental instructions use an economic frame (instructions use economic terms such as "firm," "market," and "price") (Huck et al., 2004, p. 106).

the production sector into five farms (each managed by one subject), and making soil improvement decisions endogenous. Thus, the version of the model used for our study differentiated between sectors that were subject-specific (e.g., the farm sector) and sectors that were general (e.g., the aggregated market), in which the subjects interacted. The parameter values in the study were identical to those in the maize market model described earlier (Gerber 2016), which was calibrated to country-specific data.

A central construct in the experiment was dynamic farm endowment, in which the current budget $B_{i,t}$ for subject i

$$B_{i,t} = P_{t-1} \times Pr_{i,t-1} \times Sps_{i,t-1} \times BSp \tag{1}$$

is determined by the market price P_{t-1}, a subject's production $Pr_{i,t-1}$, the share of the subject's production that is sold $Sps_{i,t-1}$ in the previous round (since sub-Saharan Africa's smallholder farmers typically self-consume part of their production) and BSp, a constant share of the total farm income that is allocated to two production activities. BSp is set at 0.25. In each round, the subjects decide how to allocate the given budget $B_{i,t}$ to the two production activities "fertilizer purchase" and "organic matter incorporation to the soil" on their farms. The experiment anticipates that the total budget $B_{i,t}$ is allocated to the activities in the form of fertilizer expenditure $ExpF_{i,t}$ and soil improvement expenditure $ExpS_{i,t}$. Soil improvement expenditure $ExpS_{i,t}$ affects the subject's productivity indirectly via SOM and the change of each subject's SOM level $SOM_{i,t}$, which is defined as

$$\frac{dSOM_{i,t}}{dt} = OM_1(y_{i,t}) + OM_2(ExpS_{i,t}, C) - \frac{SOM_{i,t}}{t_{min}} \tag{2}$$

where $OM_1(y_{i,t})$ represents the plant residues of the last season's harvest, which are added to the soil as a function of the subject's yield $y_{i,t}$ and $OM_2(ExpS_{i,t}, C)$

represents the addition of organic matter to the soil. The costs C are set to ZMW[2] 117 per lima[3]. Mineralization is expressed as $\frac{SOM_{i,t}}{t_{min}}$ and represents the process that decomposes SOM and thus reduces SOM levels. The mineralization time t_{min} is set at 31 years. In the mineralization process, plant nutrients are released, taken up by maize plants and contribute to determining yields. The available plant nutrients $x_{i,t}$ are expressed as

$$x_{i,t} = \frac{ExpF_{i,t}}{FP \times AL} + n\left(\frac{SOM_{i,t}}{t_{min}}\right) \tag{3}$$

where FP is the fertilizer price, AL a subject's maize production area, and $n\left(\frac{SOM_{i,t}}{t_{min}}\right)$ is a function that represents the nutrients that are released in the mineralization process. FP is set at ZMW 550 per 50 kg bag and AL is constant at 2 ha for all subjects. The available plant nutrients $x_{i,t}$ are eventually taken up by plants and transformed into maize yield $y_{i,t}$, expressed in 50 kg bags per year per hectare in the following form

$$y_{i,t} = A \times (1 - 10^{-b \times x_{i,t}}) \tag{4}$$

where A is the yield plateau that represents the maximum maize yield under perfect factor availability and b is a model specific constant. A is set at 9 tons per ha per year and b is set to 4.03. The subject's i production $Pr_{i,t}$ is expressed in 50kg bags per year and calculated as follows:

$$Pr_{i,t} = y_{i,t} \times AL \tag{5}$$

The overall market price is calculated as

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[2] Zambian Kwachas, the local currency.

[3] Lima is a local unit used in the measurement of area; 1 lima ≈ 0.25 ha.

$$P_t = \left(\frac{a\times\sum_{i=1}^{5} Pr_{i,t}}{D(Pop)}\right)^{\varepsilon} \times RefP \tag{6}$$

where a is a constant scaling factor, $D(Pop)$ represents the market demand as a function of population, ε is a price sensitivity parameter set at -0.86 and $RefP$ constitutes a reference market price set at 1 ZMW per kg maize.

To ensure that the model resembled the subjects' own farms as much as possible, we used a more complex version, which comprised additional mechanisms to the key equations presented above. The full model, including all equations and documentation is presented in Appendix C in this dissertation. An overview of the model's core feedback mechanisms is shown in Figure 1.

In terms of dynamic decision-making, fertilizer expenditure constitutes a short-term strategy to increase yields immediately through fertilizer application and nutrient uptake (Figure 1). Soil improvement expenditure represents a long-term strategy that increases yields through building up soil organic matter. Although higher yields increase a farmer's budget for the next growing season through increased production, sales and farm income (R1 and R2 feedback loops, Figure 1), the increased yields also lead to a higher aggregated market supply and thus to a lower price, which in turn leads to lower farm income and a lower budget for the next growing season (B1 feedback loop). In the model show in Figure 1, the B1 loop partly offsets the benefits from the R1 and R2 loops through the subjects' competition. In addition to these market-centered mechanisms, the R3 loop adds plant residues to the SOM stock and plays a central role in the Zambian maize production system because SOM represents a systemic leverage point for increasing food availability and increasing the system's resilience to external shocks, such as changes in rainfall patterns or public policies.

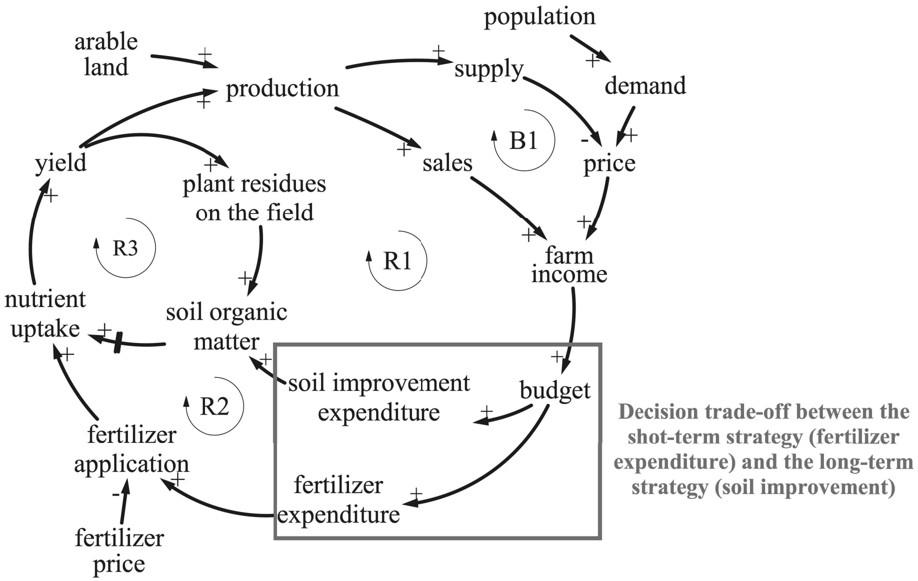

Figure 1. *Causal loop diagram of the system dynamics model.*

Notes: Arrows indicate causal relationships directed towards the arrowhead. A plus (+) at the arrowhead denotes a positive relationship (where the effect variable changes in the same direction as the cause variable) and a minus (-) denotes a negative causality (where the effect variable changes reversely directed to the cause variable). Feedback loops consist of circular chains of causal relationships and are either reinforcing processes (which self-reinforce the current behavior) or balancing processes (which adjust the behavior towards a goal). R1 – reinforcing soil improvement feedback loop; R2 – reinforcing fertilizer feedback loop; R3 – reinforcing soil organic matter feedback loop; B1 – balancing supply feedback loop.

The experiment was set to last nine rounds of four years each. In each round, decisions were collected and applied for four years in the simulation model. This allowed experiments to be conducted within a feasible amount of time and still covered a 35-year period, which was long enough for long-term processes such as soil dynamics to unfold. As performance indicator in our experiment, we used the subject's accumulated production over the total experiment duration because Zambian smallholder farmers maximize production rather than profits (Umar, 2014):

$$Performance_i = \int_0^{35} Pr_{i,t}\ dt \tag{7}$$

2.2 Experimental procedure

Our experiment followed a standard experimental economics protocol, with adjustments to match the rural and cultural context (Huck *et al.*, 2004). The main procedural adjustments were semi-computerized interaction with subjects, lack of structural transparency about the model's equations, no information about aggregated market supply, and physical rewards instead of monetary incentives (Lara-Arango *et al.*, 2017).

Due to varying degrees of literacy among the subjects, a semi-computerized approach was applied, in which experimental instructions were explained verbally in the local language following a standardized protocol (Appendix A). Important parameters to acquaint the subjects with their "experimental farm" (e.g., farm size and costs associated with the decisions) were part of the protocol and were therefore common knowledge, including symmetry across firms. Given the model's complexity and given the varying education levels in rural Zambia, we opted not to inform subjects about the market's mathematical representation. To avoid communication during the experiment, the subjects were spatially separated. For each decision-time point, the subjects received information about the current market price and their own current yield, production level and budget before the budget was allocated to the two expenditure categories: fertilizer and soil improvement. Because the rural context made a fully computerized setting impossible due to the subjects' low degree of familiarity with the use of computers and of outdoor experiments, the information was conveyed to them via record sheets (Appendix B) and communicated verbally. We opted not to inform the subjects about the aggregate market supply because such information is rarely available to Zambian farmers in everyday life. The order of the provided information was altered from round to round to avoid any order-driven bias. The subjects' decisions were noted and the information later entered into a laptop, and the simulation-based information was conveyed back to the subjects. After the completion of the experiment, a debriefing session helped farmers to reflect on their decision strategy and revealed qualitative information about their decisions. Specially trained field assistants[4] guided the experimental interaction process in the local language. The field assistants helped the subjects to understand the provided information, but strictly avoided advising the subjects on decisions and revealing structural properties of the decision context.

Prior to the experiment, we incentivized the subjects by presenting five standardized, physical rewards that they needed in everyday life,[5] and told them that the subject with best performing farm could choose a reward first, then the second, and so forth until only one reward remained for the last subject. Physical rewards were preferred over monetary rewards because of the legal and cultural context. A "game" with monetary rewards would probably have been interpreted as gambling, for which we would have needed a concession. In addition, such an approach would most likely have distracted the subjects' farming mind-set, which we wanted to analyze. According to Kelly et al. (2015), rewarding based on the performance position within the group acknowledges the subjective normative judgment of different items. The subjects were instructed that their farms' performance would be measured in accumulated production (Equation 7). This reflected Zambian smallholder farmers' production objectives, which mainly focus on covering household needs instead of profit maximization (Umar, 2014). The duration of the experiment was approximately 90 minutes.

The structural and procedural deviations from the standard protocol published by Huck *et al.* (2004) imply that it is not feasible to draw conclusions about the

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[4] The field assistants were local people who were trained in three steps: (1) They took part in the experiment as subjects, (2) they made supervised introductions and data collection among themselves, and (3) they were supervised and received feedback in the real experimental setting.

[5] 2 kg sugar, 1 kg sugar, 750 ml cooking oil, big bar of laundry soap and small bar of laundry soap.

rationality of decision-making and thus compare our results with previous studies. Instead, our main contribution lies in the analysis of empirical decisions in a dynamic context.

2.3 Subjects

The experiments were conducted in August 2016, in villages around Mumbwa, in Zambia's Central Province, where the main language spoken is Tonga. The subjects were recruited from smallholder farm communities and were either couples or widows who ran farms. Thus, all subjects were real decision-makers on farms. However, they did not have any previous experience of related experiments.

A total of 15 experiments were conducted, with 75 subjects, of whom 50 were couples and the remaining 25 were single. None of the subjects participated in more than one experiment. Through the oral and written communication, we ensured that the subjects understood the farm and market information we gave them. The subjects were motivated to take part in the experiment and made their decisions carefully. Many subjects made calculations on mobile phones or sued pen and paper, or even on sandy soil. From the subjects' reactions during the presentation of the reward items and the award ceremony, it was clear that the physical items had motivated the subjects to perform well. The reward items were chosen in varying orders (e.g., the best performing subject of some experiments chose 2 kg sugar, whereas in other experiments the best performing subject chose 750 ml cooking oil). This indicates differences in subjective normative judgments of the items.

2.4 Analysis of decisions

The subjects formulated decisions on fertilizer and soil improvement expenditure in absolute terms, as they would do on their farms in real life. However, the dynamic nature of decision-making, which is a key conceptual element in this article, meant that it was not possible to compare their decisions in absolute terms. The incomparability arose from the dynamic and endogenous interplay between subjects' decisions; which made one subject’s budget dependent on the other subjects’ decisions (Equations 1 and 6). Thus, to make the decisions comparable, we analyzed their expenditure relative to their given budget. During the debriefing sessions, some subjects even explicitly expressed that their reasoning behind their decisions was relative, as reflected in statements such as “we balanced the expenditure between the two activities.” Thus, in the following analyses we focus on fertilizer expenditure relative to the budget:

$$rEF_{i,t} = \frac{ExpF_{i,t}}{B_{i,t}} \tag{8}$$

where $rEF_{i,t}$ is the relative fertilizer expenditure, and the relative expenditure spent on soil improvement is the remaining share of the budget.

3. Results

3.1 Fertilizer expenditure decisions of the subjects

We first analyzed the share of the budget allocated to fertilizer and soil improvement, respectively, to find out whether there was a clear tendency towards one of the options. For this initial analysis, the dataset consisted of 675 decisions resulting from 15 markets, with 5 subjects in each market, and 9 decision points over the course of the experiment. The focus in this section is on the general decision-making patterns across all markets and subjects, rather than the results of a detailed analysis of individual markets and time-dependent decisions, which we present later.

The distribution of the 675 decisions is summarized in Figure 2. In 48 cases (7%), the decision was to allocate 30% or less of the budget to fertilizer purchases. In 103 cases (15%), fertilizer expenditure was between 30% and 60% of the budget, and in 524 cases (78%), the fertilizer purchases constituted of 60% or more of the budget. This indicates that the subjects had a tendency to allocate larger amounts of their budget to the short-term option (fertilizer purchases) than to the long-term option (soil improvement).

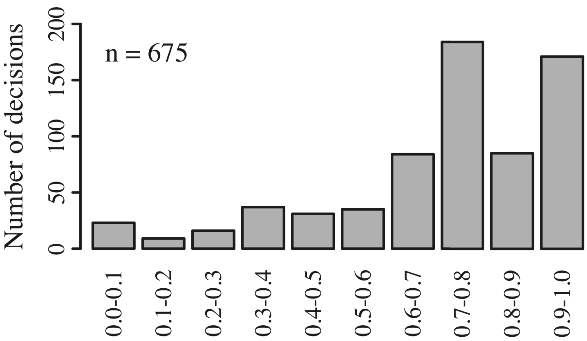

Figure 2. *Distribution of fertilizer decisions.*

To investigate the tendency towards the short-term option further, we analyzed whether there was a systematic bias towards fertilizer expenditure. We conducted two-tailed Mann-Whitney tests to analyze mean differences for the whole sample, the markets and the subjects. The null hypothesis was that the mean relative fertilizer expenditure was equal to 0.5, meaning that subjects in the respective groups had no bias towards one of the expenditure categories:

$$H_0: \mu = 0.5$$

The alternative hypothesis was that subjects in the respective groups were biased towards one of the expenditure categories:

$$H_A: \mu \neq 0.5$$

The results are summarized in Table 1 and they indicate that over the whole sample, subjects were significantly biased towards fertilizer expenditure (p value < 0.01). Additionally, the analysis of the markets revealed that all 15 individual markets showed a significant bias towards fertilizer expenditure (p value < 0.01).

Table 1. *Summary of the fertilizer allocation decisions per market. Indication about bias towards fertilizer is based on Mann-Whitney test.*

Market (M)	**Mean relative fertilizer expenditure**	**Std. Deviation**	**Number of decisions**	**Bias towards fertilizer[a]**
M1	0.75	0.240	45	yes ***
M2	0.69	0.233	45	yes ***
M3	0.69	0.263	45	yes ***
M4	0.59	0.319	45	yes ***
M5	0.73	0.220	45	yes ***
M6	0.57	0.362	45	yes ***
M7	0.85	0.133	45	yes ***
M8	0.71	0.184	45	yes ***
M9	0.77	0.182	45	yes ***
M10	0.64	0.253	45	yes ***
M11	0.84	0.182	45	yes ***
M12	0.68	0.207	45	yes ***
M13	0.69	0.134	45	yes ***
M14	0.74	0.177	45	yes ***
M15	0.81	0.133	45	yes ***
Totals	0.72	0.237	675	yes ***

Notes: [a] Significance levels: *** $p < 0.01$, two-tailed; ** $p < 0.05$, two-tailed; * $p < 0.1$, two-tailed.

While the market analysis revealed a clear bias towards fertilizer purchases, the Mann-Whitney test of the individual subjects' decisions revealed a more nuanced picture: The mean value of the relative fertilizer expenditure of 60 subjects (80%) was significantly higher than 0.5, which indicated a bias towards fertilizer expenditure (Table 2). The mean value of the relative fertilizer expenditure of 7 subjects (9%) was significantly below 0.5, thus indicating a bias towards soil improvement. For 8 subjects (11%), H_0 could not be rejected indicating that they had no bias.

Table 2. *Distribution of subjects with biases. Each subject appears only once, in the category with the lowest applicable p-value.*

Bias	**p < 0.01**	**p < 0.05**	**p < 0.1**	**Total**
Bias towards fertilizer	53	7	0	60
Bias towards soil improvement	6	1	0	7
No bias				8
Totals				**75**

3.2 Decision trajectories and benchmark

To analyze the variation in the subjects' biases more closely, we investigated the decision trajectories. Figure 3 shows the decision trajectories of all subjects within the 15 markets and the variation between the subjects' decision trajectories, and between the markets. Unlike other Cournot market-based studies that have analyzed subjects' rationality, we did not focus on theoretical equilibriums based on structural transparency, such as the Cournot Nash equilibrium or the competitive equilibrium. Instead, we calculated a near-optimal decision pattern using a Powell hill-climbing algorithm (Figure 3, top left corner). The resulting benchmark trajectory led to the highest accumulated production under the premise that all five subjects stuck to the same decision trajectory. Due to endogenous interactions, this benchmark did not represent a global optimum. However, it provided the means for comparing the empirical decision trajectories. The benchmark revealed that the highest accumulated production was achieved if a subject first chose a balanced expenditure strategy that slightly prioritized soil improvement to build up SOM stocks (R1 loop, Figure 1) and only in the last two rounds allocated the entire budget to fertilizer purchases in order to boost short-term production (R2 loop). Thus, theoretically, and from a rationality point of view, one could expect "end game behavior" to occur. However, we did not expect that to happen because we did not provide structural transparency, which is the basis for a fully rational decision-making. Figure 3 reveals that "end game behavior" was not an issue from a practical point of view.

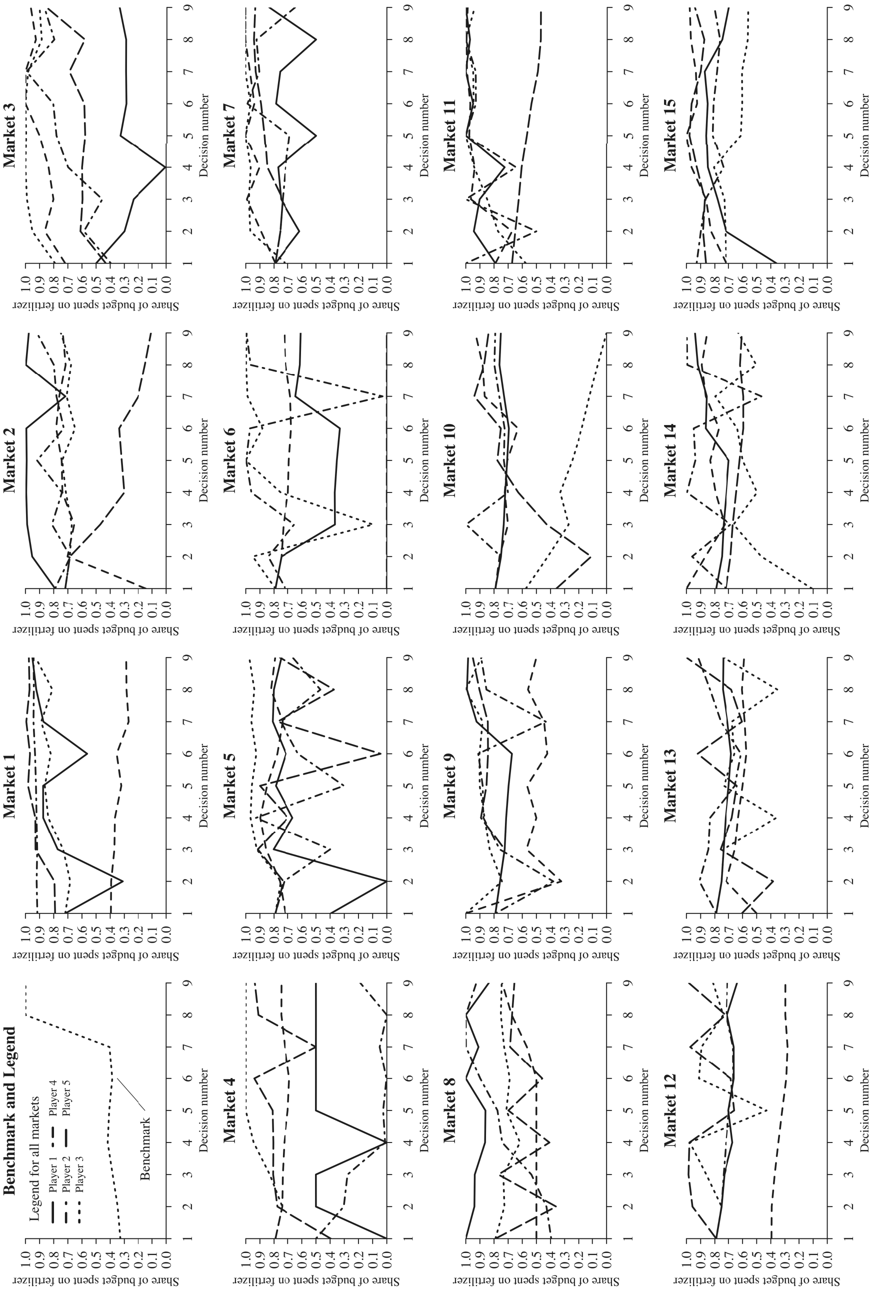

Figure 3. *The subjects' decision patterns grouped according to the markets.*

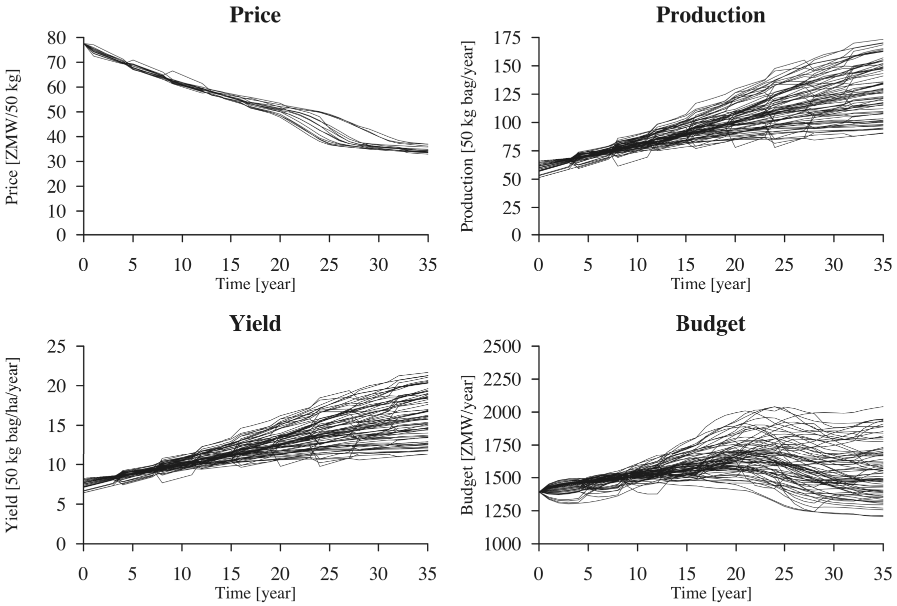

Figure 4. *Trajectories of key variables in the experiment.*

The performance among subjects and markets varied. This variation did not only result from individual subject's decisions but also from the interaction between subjects within a market. Figure 4 shows that the model was parameterized such that yield and production followed an increasing trend and price drops throughout the experiment. All the subjects started with the same initial conditions with regard to budget, farm size and costs. However, for the duration of the experiment, the subject-specific variables production, yield, and budget showed increasing variation. Subjects who initially allocated a large share of their budget to soil improvement had smaller harvests (production) at the beginning of the experiment than subjects who allocated large shares of their budget to fertilizer purchases. This was because building up SOM is a slow process with a delayed effect on yields (R1 loop, Figure 1). In the model, once the SOM stock levels are built up, the R1 loop drives up yield and production. By contrast, subjects who focused on fertilizer purchases built up SOM levels mainly through the R3 loop, which was much less effective than R1. As a result, fertilizer-centered decisions resulted in lower production towards the end of the experiment. Decision trajectories that do not only focus on one of the two alternatives and that even shift the focus throughout the experiment may lead to similar overall performance as calculated by Equation 7, despite distinctly different patterns.

3.3 Strategies

The subjects' biases towards certain expenditure categories in combination with the varying decision and performance patterns revealed in Figure 3 and Figure 4 led us to investigate the mechanisms linking decisions and performance further. In the first step, we analyzed the subjects' decisions to identify distinct decision strategies. A hierarchical cluster analysis using squared Euclidean distance as a clustering criterion was applied in order to group the decision trajectories based on relative fertilizer expenditure. The cluster analysis revealed 10 clusters that included between 2 and 16 subjects each (Figure 5).

In the second step of the analysis, we linked the clusters to performance. The performance of a subject was the result of endogenous interactions within markets, and therefore direct comparison between subjects in absolute terms—for example, of a subject's accumulated production (AP)—was limited. To analyze performance differences between the strategies, we complemented the absolute concept AP with the relative performance concepts "subject's rank within their market" (rank) and "subject's market share of accumulated production within the market" (relative accumulated production, rAP). Table 3 lists the significance levels of the two-tailed Mann-Whitney tests, which analyzed whether the means of subjects' rAP within one cluster differed from the means in other clusters. The analysis revealed that the majority of clusters differed significantly from each other in terms of performance. Clusters that did not reveal a significant difference in means either included a small number of subjects (n) or had similar performance outputs following different decision strategies. The latter can be explained by model dynamics that, in some cases, lead to similar performances, even when different strategies are applied. When we used the other performance indicators (rank and AP) for the analysis of means, we obtained very similar results to those presented in Table 3.

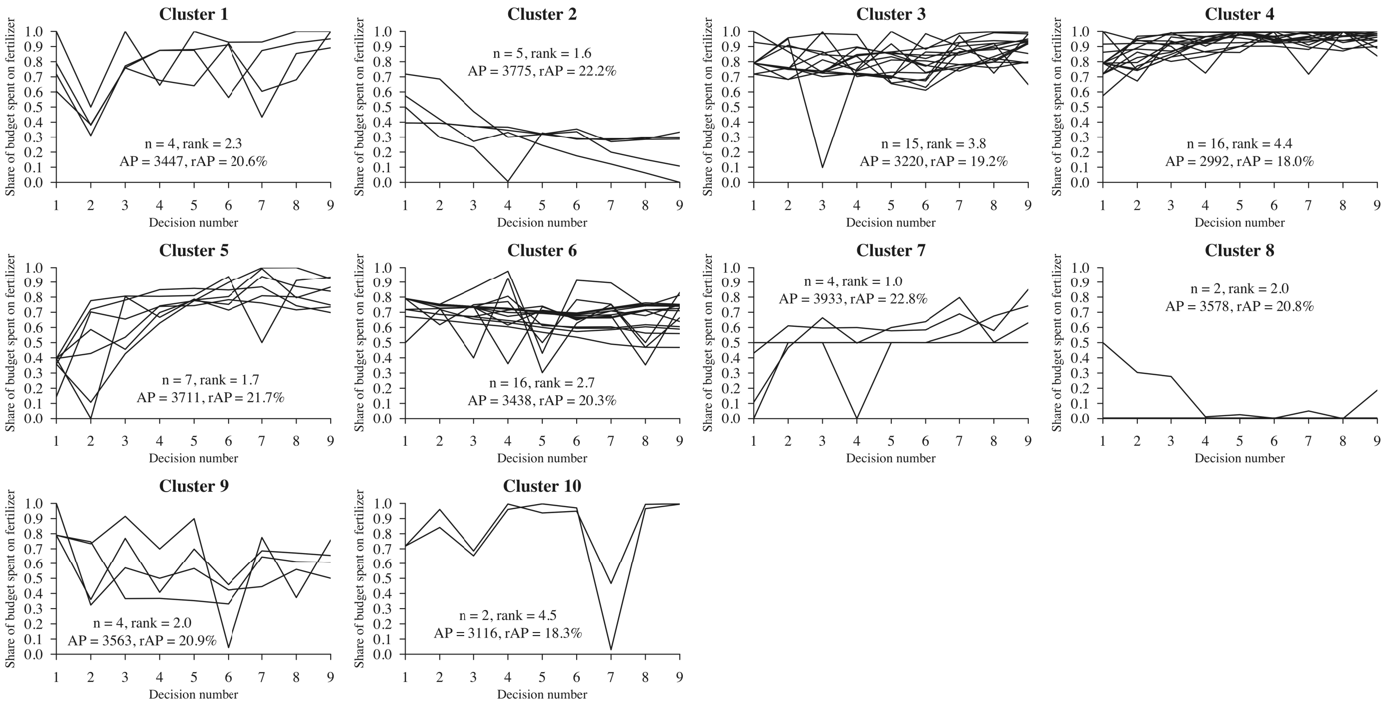

Figure 5. *Overview of the decision patterns and average values of performance indicators in the different clusters.*

Notes: n – number of subjects included in the cluster; rank – average rank of the cluster's subjects in their respective market; AP – average accumulated production of the cluster's subjects in their respective market; rAP – average relative accumulated production (market share) of the cluster's subjects in their respective markets.

Table 3. *Number and share of subjects in clusters, performance indicators and difference in means of relative accumulated production among clusters (C).*

	n^a	Share	Rank^a	AP^a	rAP^a	Different means of rAP, Mann-Whitney test^b								
						C1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
C1	4	(5%)	2.3	3447	20.6%									
C2	5	(7%)	1.6	3775	22.2%	-								
C3	15	(20%)	3.8	3220	19.2%	**	***							
C4	16	(21%)	4.4	2992	18.0%	***	***	***						
C5	7	(9%)	1.7	3711	21.7%	**	-	***	***					
C6	16	(21%)	2.7	3438	20.3%	-	**	**	***	**				
C7	4	(5%)	1.0	3933	22.8%	**	-	***	***	-	***			
C8	2	(3%)	2.0	3578	20.8%	-	*	**	**	-	-	-		
C9	4	(5%)	2.0	3563	20.9%	-	-	**	***	-	-	**	-	
C10	2	(3%)	4.5	3116	18.3%	-	*	-	-	*	**	-	-	-

Notes:

[a] For explanation see Figure 5;

[b] significance levels: *** $p < 0.01$, two-tailed; ** $p < 0.05$, two-tailed; * $p < 0.1$, two-tailed.

The analysis of the number of subjects within the clusters revealed that successful clusters (rank ≤ 2; C2, C5, C7–9) included fewer subjects (n = 2–7, 22 subjects in total), who on average allocated 50% of their budget to fertilizer purchases. Clusters with an average rank higher than 2 (C1, C3, C4, C6, C10) included more subjects (n= 2–16, 53 subjects in total), who allocated on average 81% of their budget to fertilizer purchases. Thus, few subjects chose a successful long-term strategy (soil improvement) compared to many subjects who focused on a short-term oriented strategy (fertilizer purchase) that performed worse. The successful clusters all revealed strategies that put more weight on soil improvement than on fertilizer purchases at one point in time. In this way, the subjects built up their SOM stocks and performed well, even if they applied a fertilizer-centered strategy (e.g., towards the end of the experiment, as in the case of cluster 5). Subjects in the less successful clusters predominately focused on fertilizer expenditure and thus neglected to build up SOM levels.

3.4 Heuristics

Since the subject's choice of decision strategy would have performance implications, we investigated the decision rules within the different strategies (clusters) and formulated each cluster's specific heuristic. In this context, we use the term "heuristic" to describe a mathematical decision rule that was based on the information provided to the subjects prior to the decisions. A heuristic thus represents a rule of thumb to describe how subjects made their decisions. Research has shown that linear models of decision-making often provide good representations of underlying processes (Gary and Wood, 2011). In the absence of prior information about Zambian farmers' decision rules in the context of short-term and long-term production decisions, we applied a linear regression model to estimate the decision rule for each subject:

$$rEF_t = c_1 + a_1 P_{t-1} + a_2 Pr_{t-1} + a_3 y_{t-1} + a_4 B_{t-1} \tag{9}$$

where c_1 is a subject-specific constant and a_x is the subject-specific regression parameters. We included all information cues that were presented to the subjects on the record sheet prior to each decision (price, production, yield and budget; see Appendix B). For each subject, we conducted a linear regression and obtained the subject-specific intercept c_1 and information weights a_x that specified the subject's heuristic according to Equation 9. The heuristics captured the majority of the variance in subjects' decisions with a mean R square value of 0.69.

Based on the subject-specific heuristics, we formed the aggregated heuristics of the different clusters. Accordingly, for each cluster, we calculated the strategy's specific heuristic by averaging the regression coefficient of its subjects. As a result, a cluster's heuristic was structured in the form of Equation 9, with parameter c_1 as the cluster's intercept and a_x as the respective information weights (Table 4).

Table 4. Heuristics identified in the clusters (C).

	Relative fertilizer expenditure heuristics[a]					**n**[b]	**Rank**[b]	**AP**[b]	**rAP**[b]
	Price	Production	Yield	Budget	Intercept				
C1	0.0117	0.0507	-0.2857	-0.0008	-0.0106	4	2.3	3447	20.6%
C2	0.0144	0.0041	-0.0026	-0.0001	-0.6703	5	1.6	3775	22.2%
C3	0.0279	0.0291	-0.0344	-0.0008	-1.6187	15	3.8	3220	19.2%
C4	-0.0038	0.0017	-0.0087	0.0003	0.6826	16	4.4	2992	18.0%
C5	-0.0465	-0.0353	0.0845	0.0013	3.5714	7	1.7	3711	21.7%
C6	0.0057	0.0046	-0.0007	-0.0006	0.9218	16	2.7	3438	20.3%
C7	-0.0341	-0.0056	-0.0590	-0.0003	3.8432	4	1.0	3933	22.8%
C8	0.0088	0.0056	0.0023	-0.0013	1.0445	2	2.0	3578	20.8%
C9	0.0100	0.0199	-0.1390	-0.0009	1.0280	4	2.0	3563	20.9%
C10	0.0317	0.0466	-0.1314	-0.0015	-1.2520	2	4.5	3116	18.3%

Notes:
[a] Mean information weights for the decision heuristics;
[b] For explanation see Figure 5.

Our interpretation of the heuristic's coefficients was not trivial. Some of the clusters included only a small number of subjects and were therefore limited in terms of coefficient validity. In addition, the absolute comparability of clusters was limited because the strategies originated from market-specific, endogenous interactions among the subjects. Moreover, the different information cues had different numerical ranges. In our interpretation of Table 4, we therefore mainly focus on the overall results and the relative strength of information weights within information cues and the algebraic signs of information weights between information cues.

In Table 4, most of the budget information weights have a negative algebraic sign, which indicates that most decision strategies allocated smaller shares of the budgets to fertilizer purchases if the budgets increased (except for clusters 4 and 5). The information weights of price and production have the same algebraic sign (except for cluster 4), whereas the information weight of yield has the reverse algebraic sign (compared to price and production, except for cluster 7). The interpretation of the reverse algebraic signs of production and yield is difficult, because production is a linear function of yield with a positive multiplier (Equation 5). Explanatory hypotheses can be derived from the subjects' remarks in the debriefing sessions. Some subjects indicated that, through the experiments, they had learned to differentiate between the two concepts "yield" and "production". Thus, if that was true for the majority of subjects, they might not have completely understood the positive correlation of the concepts and therefore they might have given reverse weights. Another point commonly made in the debriefing sessions was that the subjects had learned about the importance of dynamic bookkeeping. Thus, they many not have been used to applying dynamic heuristics based on farm-specific and market-specific information.

To investigate these hypotheses and to understand the heuristics better, we analyzed individual clusters. In the following, we highlight selected clusters that we found particularly interesting and that included more than 5 subjects—clusters 3–6. In clusters 3–6, cluster 4 performed worst on all performance indicators (rank, AP and rAP). Compared with the other three clusters, all information weights were relatively close to zero in cluster 4, which indicates that subjects within this cluster made decisions without giving much attention to the development of farm and market information. In addition, Figure 5 shows cluster 4 as strongly biased towards fertilizer purchases. Thus, cluster 4 followed a non-dynamic, a priori defined fertilizer strategy, which one of its subjects summarized by saying: "fertilizer works. We spent large shares of the budget to fertilizer purchases and didn't care about the other option." This supports the hypothesis above, that subjects in cluster 4 did not base their decisions on dynamic farm and market information.

Cluster 6 was similar to cluster 4, in that of no weight was assigned to farm and market information. However, Figure 5 shows that the subjects of cluster 6 applied a strategy of balanced expenditure with a moderate bias towards fertilizer purchases. This resulted in an average production that outperformed the low production of cluster 4. This finding also supports the hypothesis that farmers do not decide based on dynamic farm and market information. The subjects of cluster 6 expressed that they balanced their expenditures between the two production activities.

Of the remaining two clusters, one was among the most successful with regard to performance (cluster 5) and the other was among the least successful clusters (cluster 3). Both clusters gave relatively high weights to the provided farm and market information. However, the algebraic signs differed for all the weights. The successful subjects in cluster 5 started with comparatively low fertilizer expenditures, which means that they initially focused on the long-term strategy (soil improvement). Then, the subjects of cluster 5 decided adaptively, i.e., dynamically, based on the development of the information cues. By contrast, the subjects in cluster 3 started with relatively high fertilizer expenditures and increased the share of fertilizer expenditures even further, based on their dynamic decisions strategies. Thus, they even amplified their bias towards fertilizer expenditure. For both cluster 3 and cluster 5, which applied dynamic heuristics based on the provided farm and market information, we were not able to find explanations for the reverse algebraic sign of the information weights for yield and production, other than the hypothesis that the subjects might not have completely understood the positive correlation of the concepts. However, both clusters applied dynamic heuristics based on the provided farm and market information, but revealed highly significant differences in their performance indicators (Table 3).

3.5 Robustness of heuristics

The formation and analysis of the heuristics described above happened under the premise that the underlying data were the result of dynamic interactions among the subjects within the respective markets. Especially the heuristics of clusters with few subjects may have been biased due to the endogenous nature of the experiment. To test for robustness, we performed simulations with the heuristics presented in Table 4. Instead of the subjects making the decisions (as in the experiments), we implemented the heuristics into the simulation model and ran it for each cluster. By applying the same heuristic for all five farms, we tested how the heuristics worked in isolation. Figure 6 shows that the heuristics in Table 4 and their performance implications are robust to the experiments' endogenous interactions in most cases. In most of the clusters, the simulated allocation decisions were very similar to the average decision trajectories from the experiments. Also, the simulated accumulated production per subject (APsim) was very close to the AP in most cases (the difference was less than 3%). Only clusters 5 and 7 revealed larger differences in decision trajectories and performance. While the simulated patterns of decision trajectories still showed an increasing trend (as the empirical trajectories), the increase was exaggerated in the simulation. This exaggerated the bias towards fertilizer and resulted in APsim 9% below AP in both cases. The exaggeration of the bias happened because the heuristics highly weighted price development. When the strategies used by subjects in clusters 5 and 7 were applied in combination with other strategies, they performed well (Table 4). However, their exclusive appearance in a market created endogenous interactions that led to a suboptimal output, because high production resulted in price decreases that triggered a shift towards a fertilizer-centered strategy. This indicates that, in some cases, the composition of strategies within a market matters for a strategy's performance.

To test the effect of strategy composition within a market, we conducted further simulations with combinations of selected heuristics. The results indicated that heuristics, which led to decision patterns similar to the subjects' empirical decision means shown in Figure 6, showed little variance in production, even with varying strategy compositions (e.g., heuristic 4 in Figure 7). However, the heuristics of clusters 5 and 7 that showed divergence from empiric pattern means in Figure 6, also revealed varying production patterns, depending on the strategy composition within the market (e.g., heuristic 5 in Figure 7). Thus, the performance of heuristics 5 and 7 was strongly influenced by endogenous interactions with other subjects, which was not the case for the other heuristics.

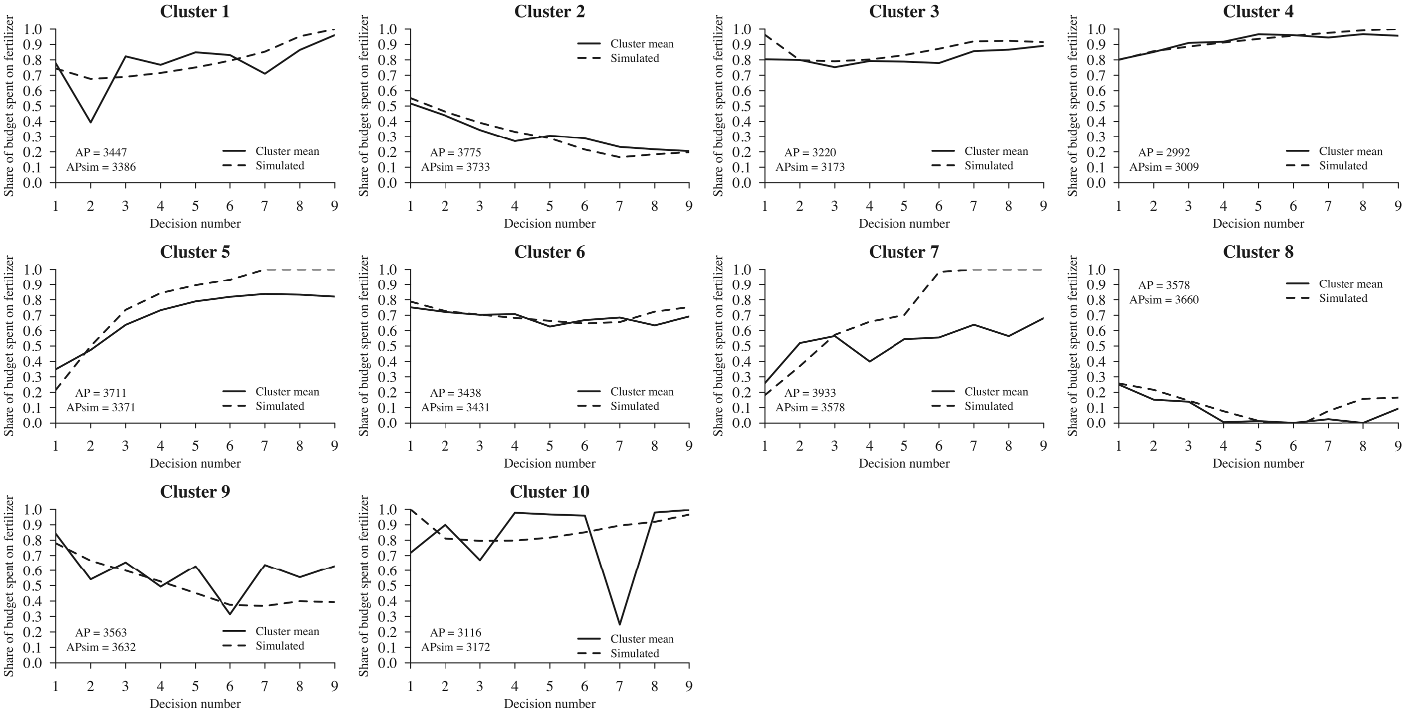

Figure 6. *Simulated heuristics versus the mean decisions per cluster.*

Notes: AP – average accumulated production of the cluster's subjects in their respective market; APsim – average accumulated production of the cluster's subjects based on simulation.

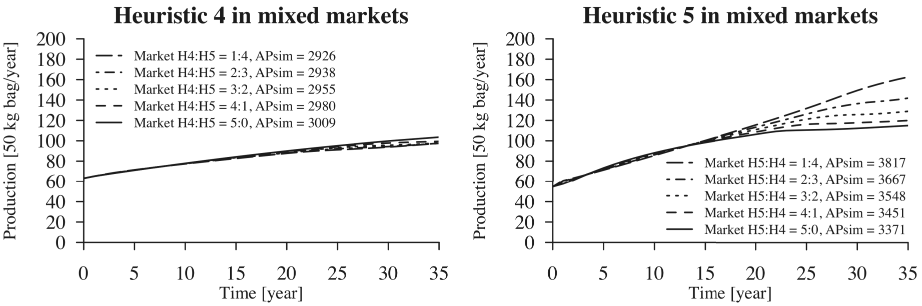

Figure 7. *Simulated production of heuristic 4 (H4) and heuristic 5 (H5) in varying combinations.*

Note: APsim – average accumulated production of the cluster's subjects based on simulation.

4. Discussion and conclusions

Smallholder farmers in sub-Saharan Africa repeatedly face situations of complex and dynamic budget allocation trade-offs between short-term and long-term production activities. Short-term activities, such as fertilizer application, help to cover immediate food needs, but they compromise future production. Long-term production activities, such as improving depleted soils, enhance future food production, but compromise current harvests. While regenerating depleted soils is an important leverage point for increasing long-term food availability, this is not a current practice. Increasing food demands will place pressure on food production systems, which will mean that soil regeneration will be unlikely to happen. We investigated Zambian smallholder farmers' decisions that governed long-term soil regeneration by using a semi-computerized, non-cooperative Cournot field experiment. In the experiment, the farmers (i.e., the subjects) aimed to maximize their maize production by repeatedly allocating a given budget to two maize production activities: fertilizer purchases (representing a short-term production strategy) and soil improvement (representing a long-term production strategy). Our results provided empirical evidence, based on the decisions of real farmers, that helped to understand the dynamic decision-making of smallholder farmers in Zambia. In the following sections, we discuss our key findings, their implications, and the potential for further research.

4.1 Bias towards fertilizer use

The results showed that, overall, the subjects had a strong and significant bias towards decisions that were effective in the short-run but decreased food system outcomes and their resilience in the long-run (fertilizer purchase). While these findings are consistent with Donovan and Casey's (1998) hypothesis that smallholder farmers had high discount rates for benefits that would be realized far in the future, our results provided empirical evidence in support of this hypothesis. The findings have both theoretical and practical implications. First, the distinct bias towards short-term strategies could be an explanatory hypothesis for why long-term policies, such as the dissemination of conservation agriculture, are difficult to scale up (Giller *et al.*, 2009). Whereas short-term policies, such as fertilizer subsidy programs (FSPs), are in accordance with the farmers’ mind-sets, long-term polices are not. Second, given the potential of long-term strategies to increase production, resilience, and sustainability, it would be crucial to scale up long-term strategies (Gerber, 2016; Stave and Kopainsky, 2015). Thus, to scale up long-term oriented strategies, a shift in farmers’ decision-making is required, for example through agricultural extension (consultancy for farmers). However, it is not straightforward what the shift in mind-set should include and how it could be achieved. The following findings may help in this respect.

4.2 Variation in decision strategies

Besides the clear overall bias towards short-term production activities, we found great variability in the farmers’ decision patterns. A non-negligible number of subjects either clearly prioritized the regeneration of soil organic matter (SOM) over short-term benefits or had no bias towards one of the expenditure categories. To analyze this variation, we structured the decision patterns into 10 clusters, each of which represented a distinct decision strategy. The number of subjects within the clusters varied. Especially the clusters that performed best in terms of production comprised a small number of subjects and at least at one point during the experiment focused on improving soil fertility. Clusters that performed worse included the majority of subjects and were centered on fertilizer purchases.

4.3 Decision dynamics and success factors

To investigate the link between decisions and performance further, we developed heuristics for each cluster in the form of mathematical decision rules based on the information cues that were provided to the subjects prior to them making their decisions. The analysis of the clusters' heuristics revealed that some heuristics that covered the majority of subjects were rather insensitive to the provided farm and market information and thus did not take into account the dynamics of the food production system. The performance of those "non-dynamic heuristics" varied and depended on a priori decision rules, which we were not able to detect due to the study design. The closer the non-dynamic heuristics were to the decision benchmark (Figure 3), the better the heuristics performed. However, some subjects reacted to the provided information and made their decisions in response to the dynamic context. The performance of such "dynamic heuristics" also varied. Heuristics that started with low fertilizer expenditures and dynamically shifted in their focus towards higher fertilizer expenditure were most successful in terms of production. Dynamic heuristics that started and remained with high fertilizer expenditure shares were less successful in terms of production. Heuristics that started with high shares of fertilizer expenditure but showed a decreasing trend over the experiment's duration led to a medium performance because the SOM stocks were built up too late to have an impact in the experiment. Thus, we found both, dynamic and non-dynamic heuristics, and both groups had varying performances.

Deciding dynamically alone does not guarantee success. Instead, we found two preconditions or drivers of success for dynamic heuristics that resulted in above-average performance in terms of production. First, the most successful subjects initially focused on replenishing SOM stocks before reaping the short-term benefits from the application of inorganic fertilizer. This criterion was necessary to trigger the food production system’s long-term leverage point. Second, successful subjects dynamically adjusted their decisions based on farm and economic information. This criterion was necessary but not sufficient to achieve a good performance. Subjects who adjusted their decisions dynamically did not perform better than other subjects, unless they prioritized soil organic matter replenishment at the outset. Thus, dynamic adjustment is only beneficial if the first condition is met.

4.4 Dynamic interaction of decision strategies

We further analyzed how the heuristics performed in terms of production if they were part of markets with varying combinations of different heuristics. Most of the heuristics revealed stable production patterns, even when the composition of heuristics within the market varied. Thus, the majority of the heuristics were robust to the endogenous interactions between different decision strategies within the markets. However, we found that two heuristics reacted strongly to market signs (prices) and that were sensitive to the interactions between decision strategies. The production pattern of those two heuristics largely depended on the other decision strategies that were present in the market. For example, accumulated production was rather low when all five farms applied the same heuristic. However, if these heuristics were part of markets that embraced a mix of decision strategies, they had the potential to lead to top performances in terms of production. This indicates that the performance of heuristics that place a strong emphasis on price information will be strongly influenced by dynamic and endogenous interactions within the respective markets.

4.5 Practical implications

Overall, a shift in mind-set towards favoring long-term production activities is needed to increase sub-Saharan Africa’s food production sustainably. Our findings revealed relevant information for agricultural extension, which in practice may facilitate such a shift. The observed variation in decision strategies means that there may not be a single solution for all cases. Instead, agricultural extension should design interventions with the potential and flexibility to take into account diverse decision strategies within a group of farmers. In that way, agricultural extension could build on current practices instead of introducing radical paradigms or, in some cases, completely new ones.

The two drivers of success have further implications for practice. The first driver of success—initially prioritizing the replenishment of SOM stocks—takes considerable time to increase production substantially. This creates a severe conflict with the need to secure short-term benefits (immediate food needs) through the use of inorganic fertilizer. Thus, an important prerequisite for implementing a strategy designed to replenish SOM might be to explicitly combine it with the application of inorganic fertilizer in order to reduce the trade-off between short-term and long-term objectives (Kearney *et al.*, 2012).

Concerning the second driver of success, the dynamic adjustment of decisions, our data show that it is quite uncommon for farmers to adjust their decisions dynamically to economic information, such as prices. However, Spicer reports that in-depth interviews with smallholder farmers in Zambia revealed that they were very capable of adjusting their decisions dynamically in other domains (Spicer, 2015). For example, farmers used agronomic information that enabled them to decide about biological production aspects, such as crop rotation. The implementation of the second driver of success can thus build on what farmers already do, which is to adjust their decisions dynamically based on agronomic information, and use this for comparison when making decisions that need to include economic information.

Another challenge for implementing the second driver of success arises from the endogenous interactions between decision strategies within a market. Our analysis revealed that the performance of some dynamic heuristics was dependent on the composition of the heuristics within the markets. Such interaction-sensitive heuristics may be attractive to individual farmers because they are successful in terms of production if other farmers choose other, less successful strategies. However, from a broader perspective, dynamic heuristics that are sensitive to endogenous interaction bear the risk of performing below their potential. Thus, alternative heuristics that have a slightly lower maximal production potential but react less sensitively to endogenous interactions might be preferable. These insights further highlight the need for context-specific extension services, and in general it should be emphasized that there is no universal optimal way for smallholder farmers to make and dynamically adjust decisions. This reinforces the need for building adaptive capacity rather than promoting the broadest possible diffusion of technical training.

4.6 Further research

Findings from experimental studies are not conclusive in the sense that they originate from a laboratory environment and not from a real-world context. The external validity of experiment-based findings is thus a common concern and ultimately needs empirical confirmation based on real world data. However, previous research has shown that the external validity of experimental findings allows for some generalization (e.g., Anderson *et al.*, 1999) and we believe that our experimental setup, which was as close as possible to the subjects' situation on their respective farms contributed to the potential for external validity of our findings. In particular, the use of a complex model that included time delays and feedback processes, and that was calibrated using data from Zambia, allowed us to mimic farmers' real-world decision tradeoffs. The external validity of our findings is further supported by the field experiment setting, in which real farmers were subjects (Lara-Arango *et al.*, 2017).

Although we have revealed insights into the dynamic decision-making of sub-Saharan Africa's smallholder farmers in the context of short-term and long-term production activities with conflicting objectives, there are several ways in which our findings could be expanded and complemented. We found that some of the subjects decided on a priori heuristics that we could not explain with our study design. However, to develop agricultural extension towards long-term production activities, knowledge of the foundation of a priori heuristics might be useful. Our study design could be enriched by individual, semi-structured interviews with all subjects after the completion of the experiment. Such interviews would allow qualitative information about the a priori heuristics to be gathered, but might also be a means to explore why even dynamic heuristics reveal reverse algebraic signs for the information weights of yield and production.

Further research should address the process of decision-making. Our subjects consisted of couples and single players, and exploratory analysis of our data revealed that neither their performance nor their decision about strategy was affected by these facts. However, couples mentioned in the debriefing sessions that they were not used to decide together. Thus, investigating on-farm decision processes with regard to performance might both inform agricultural extension about key decision persons and be useful for evaluating the external validity of the findings. In sum, our results provide important evidence of dynamic decision-making by farmers to enhance food availability sustainably in sub-Saharan Africa and serve as a steppingstone for further research in this field.

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Appendixes

Appendix A: Data Gathering Protocol

1. Gather the participants (5 couples, that in real life each actually run a farm together).

2. Introduction and Instructions: Hello and welcome everybody.

Introduction of all that are present

A. Purpose

Thank you for being here. Today we gather information for learning how you make different decisions. Andreas is doing a schoolwork study for his PhD in collaboration with Dr. Nyanga at UNZA[6]. He is interested in learning how you make decisions as couples. The information will be used for academic purposes and may be published in academic journals. Is that clear and ok for you?

B. Roles

We would like to gather the information through playing a game together. The roles are: I am the moderator, who will interact with you. Andreas is the computer man, who will be putting the information in the computer and giving the results. Cain and Eukeria will help me moderating the process, transmitting information between you and the computer man. You, the couples, are the players who make decisions.

C. Game

Every couple will manage a farm. You all have a common main goal for your farm. In this game the main goal is to maximize your accumulated maize production over the whole game. To reach the goal of maximize your production, you must decide how much money (Kwachas) you want to spend on two options. The first option is buying own fertilizer (not through government or NGO subsidies). And the second option is spending financial means to improve your soil through crop residue retention and manure application. In this game we just have these two options and we

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[6] University of Zambia

are not considering other options such as lime application, crop rotation, Musangu tree plantation, etc.

Here is some information to understand your farm: Each couple cultivates 8 limas (equivalent to 2 hectares) of maize on its farm, so your decisions are limited to this area. The maize yield level is currently around 7 bags of 50kg per lima; the current/starting production therefore is around 60 bags of 50kg per farming season. The current/starting producer price of maize at your market is around 75 Kwacha per 50kg bag.

In the beginning your budget for the two options is 1392 Kwacha. In the first option, which is buying fertilizer, a 50 kg bag of fertilizer cost 550 Kwacha. In the second option, which is crop residue retention and manure application, a lima costs you 117 Kwacha, adding external organic matter becomes more expensive.

For you to make decisions, the moderator will come to you and give you information about your budget, yield, current production and market price. You will then decide how much of the budget you want to spend on fertilizer and how much you want to spend to improve your soils. The moderator will take note of your decision and bring it to Andreas. He will put your decision into the computer and calculate the new budget, yield, production and price. The moderator will bring this new information back to you so that you can again decide how much money you will spend for fertilizers and soil improvement. We will have 9 rounds in this game. Thus, these dynamics will continue until we complete 9 periods (you make 9 decisions). The game will be completed in 1-2 hours approximately.

At the end of the game, the computer calculates your total production for the entire game and you will be rewarded with a present depending on your results. We brought a couple of items of which the best performing couple can choose one item first, the second best performing couple second, etc.

Show the goods (2kg sugar, 1kg sugar, 750ml oil, big laundry soap, small laundry soap)

If you have difficulties to make your decision, think of how you decide on your own, real farm and always keep in mind that your goal is to maximize your production!

We will have the possibility to clarify procedural questions during the game, but not ask for help in decision making. So far, is the game clear to you? Are you willing to participate? If you do not want to participate or feel uncomfortable, you can withdraw.

Remarks to the instructor:

It is ok to clarify procedural questions: e.g., what happens after we make a decision? Do we have to spend the entire budget to these two policies? Etc.
It is also ok to clarify the meaning of words (e.g., yield)
Do not give clues that may directly influence the decision making process. E.g., do not answer questions regarding what should be done such as “should I allocate more on fertilizers?” or “How can I make the highest production in the game?”

3. Split the participants up.

In this game it is the idea that you keep your decisions and results as a secret within your farm and do not share them with the other couples. So please, keep communication between the farms at a low level. However, once the game is finished and we have all the results from everyone, you are very free to share experiences and strategies with each other!
Give your best and good luck!!

4. Start the actual rounds.

After first round: explain that yield, production, price and budget changes. Costs stay the same.

5. Save the rounds.

Take a copy (soft or hard) from the interaction sheets and save it.
Give a hard copy to the farmers as a feedback.

6. Conclude with an aftermath session.

At this point the game is over and you are free to leave if you wish. However, if you appreciate, we will have a feedback session explaining some ideas of the game.

Appendix B: Record Sheet

Farm Number:________

Name of Participants:

____

____

Data Collection Set-Nr:___

Input prices:
- 50 kg Fertilizer costs 550 ZMW
- 1 lima improved soil costs 117 ZMW, for further improvement the price increases

Round 0	Yield ≈7 bags/lima	Production ≈60 bags	Price ≈75 ZMK/bag	Budget 1392 ZMW	Soil	**Fertilizer**
1	Price	Yield	Production	Budget	**Soil**	Fertilizer
2	Production	Price	Yield	Budget	Soil	**Fertilizer**
3	Yield	Production	Price	Budget	**Soil**	Fertilizer
4	Price	Yield	Production	Budget	Soil	**Fertilizer**
5	Production	Price	Yield	Budget	**Soil**	Fertilizer
6	Yield	Production	Price	Budget	Soil	**Fertilizer**
7	Price	Yield	Production	Budget	**Soil**	Fertilizer
8	Production	Price	Yield	Budget	Soil	**Fertilizer**
9	Yield	Production	Price	Budget	**Total Production**	

Date: ______________ Place: ______________

Appendixes

Appendix A

Model Documentation Article 1

A.1 Purpose and Scope of the Model

Article 1 is based on a system dynamics simulation model with the purpose to evaluate policy options (such as fertilizer subsidy programs) in regard to their ability to increase short- and long-term food availability (in terms of kilocalories per capita). The model is of illustrative nature, it captures the key processes of the Zambian food production system on an aggregated, national level, and it runs over decades (1984-2050). Different subsectors of the food production system are represented with varying levels of detail according to their importance in the Zambian population's diet; i.e. the maize sector is fully endogenous, plant production other than maize is partly endogenous, and animal based production is represented by exogenous variables. The model structure was developed through theory integration (see Article 1) and was calibrated using data from Zambia (see below). The model was specified in Vensim software and is accessible as supplementary material on the homepage of Sustainability, the journal of publication.
Homepage: http://www.mdpi.com/2071-1050/8/10/1036; accessed 2 May 2017.

A.2 Summary Statistics of the Model

According to the Vensim software, the unit's within the model are consistent and the syntax is complete. The model was not sensitive to changes in values of the time step and integration methods.

The following summary statistics are based on the SDM-Doc tool that is available on the Systems Dynamics Society homepage (http://tools.systemdynamics.org/sdm-doc/; accessed: 25 April 2017).

Summary statistics of the model that underlies Article 1

Model information	**Result**
Total number of variables	234
Total number of stocks	10 (4.3%)
Total number of feedback loops	545
Whereof reinforcing	265
Whereof balancing	280
Total number of causal links	379
Total number of macros	0
Variables with source information	0
Dimensionless unit variables	61 (26.1%)
Variables without predefined min or max value	230 (98.3%)
Function sensitivity parameters	0
Data lookup tables	0
Time unit	Year
Initial time	1984
Final time	2050
Reported time interval	1
Time step	0.0625
Model is fully formulated	Yes
Warnings	**Result**
Number of undocumented variables	0
Equations with embedded data	15 (6.4%)
Variables not in any view	0
Nonmonotonic lookup functions	0
Cascading lookup functions	0
Non-zero end sloped lookup functions	0
Equations with if then else functions	12 (5.1%)
Equations with min or max functions	12 (5.1%)
Equations with step pulse or related functions	1 (0.4%)
Potential Omissions	**Result**
Unused variables	0
Supplementary variables	5 (2.1%)
Supplementary variables being used	0
Complex variables (more than 3 causes)	18 (7.7%)
Complex stocks	0

A.3 Model Equations

A.3.1 Yield Sector

Above ground dry matter = plant residue above ground dry matter + maize yield dry matter
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production of maize plants above ground (including all plant parts, also yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Arable Land = INTEG (arable land conversion rate - other land conversion rate, INITIAL ARABLE LAND AND PERMANENT CROPS)
Units: Ha
This stock represents the value of arable land (that is used for vegetal production, except grass). In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to settlement land. Source of reference data: calculated from FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Area harvested maize = Arable Land * share of maize on total area harvested
Units: Ha
This variable represents the area on which maize is produced. Note that one could differentiate between the area planted with maize and the area harvested with maize, etc. For simplicity I assume that they are equal and call it “area harvested maize” (to make it clear that this area is relevant for calculating the maize production).

AVERAGE NITROGEN FERTILIZER PRICE REAL 1984 TO 2011 = 621
Units: Rlc/Kg
This constant represents the future scenario for nitrogen fertilizer prices and is the calculated average of the prices during the reference period.

AVERAGE PRECIPITATION 1984 TO 2011 = 880
Units: Mm/Year
This constant represents the future scenario of precipitation and is the calculated average over the reference period.

DRY MATTER FRACTON OF MAIZE YIELD = 0.87
Units: Dmnl
This variable represents the dry matter share of maize yields (the rest is mainly water). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

EFFECT FACTOR OF NITROGEN ON YIELD = 4.03
Units: Ha*Year/Ton
This is a model and case specific constant of the Mitscherlich-Baule production function (which calculates maize yields). The constant was obtained by indirect optimization and triangulated using literature (e.g. Llewelyn and Featherstone, 1997). Source: Llewelyn R.V., Featherstone A.M. 1997. A comparison of crop production functions using simulated data for irrigated corn in western Kansas. Agricultural Systems, 54, (4), 521-538.

EFFECT FACTOR OF WATER ON YIELD = 0.004
Units: Year/Mm
This is a model and case specific constant of the Mitscherlich-Baule production function (which calculates maize yields). The constant was obtained by indirect optimization and triangulated using literature (e.g. Llewelyn and Featherstone, 1997). Source: Llewelyn R.V., Featherstone A.M. 1997. A comparison of crop production functions using simulated data for irrigated corn in western Kansas. Agricultural Systems, 54, (4), 521-538.

Effect intercept of soil organic matter on nitrogen = REFERENCE NITROGEN UPTAKE SHARE - INITIAL RELATIVE SOIL ORGANIC MATTER * EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN
Units: Dmnl

Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Effect of nitrogen on yield = 1-10^(-EFFECT FACTOR OF NITROGEN ON YIELD*nitrogen uptake by maize)
Units: Dmnl
This variable is part of the Mitscherlich-Baule production function (which calculates maize yields). More information is available in the documentation for yield.

Effect of water on yield = 1-10^(-EFFECT FACTOR OF WATER ON YIELD*water plant uptake)
Units: Dmnl
This variable is part of the Mitscherlich-Baule production function (which calculates maize yields). More information is available in the documentation for yield.

EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN = 0.2
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship

between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. The model reacts rather sensitive to this parameter. A reality check in simulation outcomes suggests a value of around 0.2. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER = 0.1
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. The model reacts rather sensitive to this parameter. A reality check in simulation outcomes suggests a value around 0.1. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Indicated nitrogen uptake share = EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN*relative soil organic matter+effect intercept of soil organic matter on nitrogen
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent

the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Indicated water uptake share = relative soil organic matter*EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER+intercept of som effect on water
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

INITIAL RELATIVE SOIL ORGANIC MATTER = INITIAL(relative soil organic matter)
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E.,

Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Intercept of som effect on water = REFERENCE WATER UPTAKE SHARE-INITIAL RELATIVE SOIL ORGANIC MATTER*EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

KG PER TON = 1000
Units: Kg/Ton
This constant represents the number of kilograms per metric ton.

Maize yield = YIELD PLATEAU*effect of nitrogen on yield*effect of water on yield
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize grain harvested on one hectare, some water remains in the grain). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). For choosing a production function, many alternatives are potentially available (e.g. square root functions, linear min-function, polynomic functions etc.). I chose a Mitscherlich-Baule production function because it is applicable on a large geographical and temporal scale, allows for factor

substitution, has empirical support and is adequate in complexity compared with the rest of the model. Because factor endowment is low in Zambia, a stage II function is acceptable (compared to a stage III function). Unlike as in the common approach, I calculate yield based on realized element uptake instead of application rates to be operational. Maize yield is a suitable variable for comparing simulation results with historical data, because yield is part of many feedback loops and historical data is reliable (FAO data was used for calibration and it was triangulated with other sources; FAO 2014). Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

Maize yield dry matter = maize yield*DRY MATTER FRACTON OF MAIZE YIELD
Units: Ton/(Year*Ha)
This variable represents the amount of dry matter in maize yields. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

MAXIMUM NITROGEN UPTAKE SHARE = 0.85
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Schilling (2000 p.435) indicates a nitrogen uptake of 65-85% in Europe. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to

cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

MAXIMUM WATER UPTAKE SHARE = 0.5
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Mineralized nitrogen = nitrogen fertilizer application per hectare maize + soil organic nitrogen mineralization rate
Units: Ton/(Year*Ha)
This variable represents the amount of mineralized nitrogen that is available in the soil. It includes nitrogen from organic and inorganic sources.

MINIMUM NITROGEN UPTAKE SHARE = 0.45
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Schilling (2000 p.435) indicates a nitrogen uptake of 65-85% in Europe. The lower bound is reduced here for the low SOM levels in Zambia. Sources: Johnston A.E., Poulton P.R., Coleman

K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

MINIMUM WATER UPTAKE SHARE = 0.05
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

NITROGEN CONTENT OF ABOVE GROUND RESIDUES = 0.006
Units: Dmnl
Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

NITROGEN CONTENT OF BELOW GROUND RESIDUES = 0.007
Units: Dmnl
Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Nitrogen fertilizer application = total nitrogen fertilizer expenditure real/(nitrogen fertilizer price real*KG PER TON)
Units: Ton/Year
This variable calculates the annual total nitrogen fertilizer application in tons.

Nitrogen fertilizer application per hectare maize = nitrogen fertilizer applied to maize/area harvested maize
Units: Ton/(Year*Ha)
This variable represents the per hectare annual nitrogen fertilizer application on maize fields.

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

Nitrogen fertilizer price real = IF THEN ELSE(Time<2012, NITROGEN fertilizer price real data, AVERAGE NITROGEN FERTILIZER PRICE REAL 1984 TO 2011)
Units: Rlc/Kg
This variable represents the development of nitrogen fertilizer prices (in real local currency: Zambian Kwacha 94). Because fertilizers include various combinations of nutrition elements, this price was calculated out of a combination of different fertilizer prices, filtered for the nitrogen component. Source: MAOC. Various years. Provincial Prices from 1994 to 2012. Ministry of Agriculture and Cooperatives, Lusaka, Zambia.

NITROGEN fertilizer price real data: INTERPOLATE
Units: Rlc/Kg
This variable represents the past development of nitrogen fertilizer prices (in real local currency: Kwacha 94). Because fertilizers include various combinations of nutrition elements, this price is calculated. Source: MAOC. Various years. Provincial Prices from 1994 to 2012. Ministry of Agriculture and Cooperatives, Lusaka, Zambia.

Nitrogen in plant residues below ground = plant residue below ground dry matter*NITROGEN CONTENT OF BELOW GROUND RESIDUES
Units: Ton/(Year*Ha)

This variable represents the total amount of nitrogen in below ground plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Nitrogen in plant residues above ground = plant residue above ground dry matter*NITROGEN CONTENT OF ABOVE GROUND RESIDUES
Units: Ton/(Year*Ha)
This variable represents the total amount of nitrogen in above ground plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Nitrogen uptake by maize = mineralized nitrogen*uptake share of nitrogen
Units: Ton/(Year*Ha)
This variable represents the average amount of nitrogen that is taken up by maize plants on one hectare throughout one growing season. Maize plants are not able to take up all mineralized nitrogen available in the soil. Thus, this variable represents a share of the total mineralized nitrogen (Schilling 2000). The uptake share of nitrogen is assumed to depend on the level of soil organic matter (Johnston et al., 2009). Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Plant residue above ground dry matter = PLANT RESIDUE ABOVE GROUND INTERCEPT+PLANT RESIDUE ABOVE GROUND SLOPE*maize yield dry matter
Units: Ton/(Year*Ha)
This variable represents the amount of dry matter residues of maize production, above ground (excluding yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. Note: units conversion Mg = Mega grams = 10^6g = 1t.

PLANT RESIDUE ABOVE GROUND INTERCEPT = 0.61
Units: Ton/(Year*Ha)
This constant is used to calculate the plant residues of maize production. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-19%.

PLANT RESIDUE ABOVE GROUND SLOPE = 1.03
Units: Dmnl
This constant is used to calculate the plant residues of maize production. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-3%.

Plant residue below ground dry matter = above ground dry matter*RATION BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production below ground (assumed that all organic matter is left in the soil as residues). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Page 11.14.

Plant uptake share of water = MIN(MAX(indicated water uptake share, MINIMUM WATER UPTAKE SHARE), MAXIMUM WATER UPTAKE SHARE)
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Precipitation = IF THEN ELSE(Time<2012, PRECIPITATION data, AVERAGE PRECIPITATION 1984 TO 2011)
Units: Mm/Year
Under the assumption of a smallholder production system, precipitation is the main source of water for crop growth (because irrigation installations are expensive). This variable represents the annual rainfall.

PRECIPITATION data: INTERPOLATE
Units: Mm/Year
This variable represents the past development of precipitation, which is calculated from data (using the values of meteorological stations in the Zambian maize areas). Source: ZMD, Monthly Precipitation Data. Various years, Zambia Meteorological Department.

RATIO BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER = 0.22
Units: Dmnl
This constant is used to calculate the plant residues of maize production. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-26%.

REFERENCE NITROGEN UPTAKE SHARE = 0.5
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R.,

Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

REFERENCE SHARE OF ABOVE GROUND PLANT RESIDUES REMOVED FORM THE FIELD = 0.7
Units: Dmnl
This constant represents the share of (above-ground) plant residues that are removed from the maize fields. These residues are eaten by animals, burned on the open field, used for construction, burned for energy purposes, etc. The value was estimated by Dr. P. Nyanga, University of Zambia, Lusaka, Zambia.

REFERENCE WATER UPTAKE SHARE = 0.1
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet well researched (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Relative soil organic matter = soil organic matter/INITIAL SOIL ORGANIC MATTER
Units: Dmnl
This variable represents the soil organic dry matter amount relative to its initial value.

Share of above ground plant residues removed from the field = IF THEN ELSE(Time<TIME OF SOIL ORGANIC MATTER POLICY IMPLEMENTATION, REFERENCE SHARE OF ABOVE GROUND PLANT RESIDUES REMOVED FORM THE FIELD, SHARE OF PLANT RESIDUES REMOVED UNDER SOIL

ORGANIC MATTER POLICY)
Units: Dmnl
This variable represents the share of above ground plant residues that are removed from the field, ether for animal feeding, through burning or for other uses.

Share of nitrogen to maize = area harvested maize/Arable Land
Units: Dmnl
This variable defines the share of total annual nitrogen fertilizer application going to maize.

SHARE OF PLANT RESIDUES REMOVED UNDER SOIL ORGANIC MATTER POLICY = 0.7
Units: Dmnl
This constant represents the share of (above-ground) plant residues that are removed from the maize fields under the soil improvement policy. By reducing this share, more organic matter is added to the soil organic matter stocks. Thus, lass residues are eaten by animals, burned on the open field, used for construction, burned for energy purposes, etc.

Soil organic nitrogen mineralization rate = Soil Organic Nitrogen/AVERAGE MINERALIZATION TIME
Units: Ton/(Year*Ha)
Soil microbes and creatures decompose soil organic matter (SOM). This variable represents the mineralization process of SOM and thus of its component nitrogen. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

TIME OF SOIL ORGANIC MATTER POLICY IMPLEMENTATION = 2012
Units: Year
This constant represents the year in which soil improvement policies are introduced (in Experiments 6,7 and 8).

Total nitrogen fertilizer expenditure real = total fertilizer expenditures real*SHARE of fertilizer expenditure on nitrogen
Units: Rlc/Year
This variable represents the annual amount of total fertilizer expenditures going to nitrogen (in real local currency: Zambian Kwacha 94).

Total nitrogen in plant residues = nitrogen in plant residues below ground+nitrogen in plant residues above ground
Units: Ton/(Year*Ha)
This variable represents the total amount of nitrogen in plant residues after harvest (excluding nitrogen in maize kernels that are removed from the field). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Total nitrogen in plant residues left on the field = nitrogen in plant residues below ground+nitrogen in plant residues above ground*(1-share of above ground plant residues removed from the field)
Units: Ton/(Year*Ha)
This variable represents the amount of nitrogen in plant residues left on the field after harvest.

Uptake share of nitrogen = MIN(MAX(indicated nitrogen uptake share, MINIMUM NITROGEN UPTAKE SHARE), MAXIMUM NITROGEN UPTAKE SHARE)
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake I apply a liner effect relationship between SOM and the nitrogen uptake share with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable

agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Water plant uptake = precipitation*plant uptake share of water
Units: Mm/Year
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet well researched (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

YIELD PLATEAU = 9
Units: Ton/(Ha*Year)
This constant is part of the Mitscherlich-Baule production function and represents the maize yield under perfect factor availability. It assumes a mixture of maize varieties (hybrid and traditional seeds).

A.3.2 Soil Orgnaic Matter Sector

Animal carbon per hectare = animal organic matter per hectare*CARBON SHARE IN DRY MATTER
Units: Ton/(Ha*Year)
This variable represents the annual amount of organic carbon applied on arable land through animal manure.

Animal organic matter per hectare = ORGANIC matter from animals/Arable Land
Units: Ton/(Ha*Year)

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

Animal organic nitrogen per hectare = ORGANIC nitrogen from animals/Arable Land
Units: Ton/(Year*Ha)
This variable represents the annual amount of organic nitrogen applied per hectare arable land through animal manure.

Arable Land = INTEG (arable land conversion rate-other land conversion rate, INITIAL ARABLE LAND AND PERMANENT CROPS)
Units: Ha
This stock represents the value of arable land (that is used for vegetal production, except grass). In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to settlement land. Source of reference data: calculated from FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

AVERAGE MINERALIZATION TIME = 31
Units: Year
This constant represents the average soil stock residence time for carbon and nitrogen. Parameter range: 10-50 years (Scheffer and Schachtschabel 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Carbon in plant residues remaining on the field = plant residues remaining on the field*CARBON SHARE IN DRY MATTER
Units: Ton/(Ha*Year)
This variable represents the total amount of carbon contained in plant residues remaining on the field.

CARBON SHARE IN DRY MATTER = 0.58
Units: Dmnl
This constant represents the carbon share in soil organic dry matter. To convert C-content into soil organic mater (SOM), one can assume an average C-concentration of 58%. The C-concentration can vary from 40 to 60%. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Carbon to nitrogen ratio = Soil Organic Carbon/Soil Organic Nitrogen
Units: Dmnl
This variable represents C to N ratio in soil organic matter.

INITIAL SOIL ORGANIC CARBON = 20
Units: Ton/Ha
This constant represents the initial value of the soil organic carbon stock.

INITIAL SOIL ORGANIC MATTER = INITIAL(soil organic matter)
Units: Ton/Ha
This variable represents the initial per hectare amount of organic dry matter on arable land.

INITIAL SOIL ORGANIC NITROGEN = 1.6
Units: Ton/Ha
This constant represents the initial value of the soil organic nitrogen stock.

NITROGEN FIXATION THROUGH SOIL BACTERIA = 0.03
Units: Ton/(Ha*Year)
This flow represents nitrogen fixation through free-living soil bacteria (excluding nodule bacteria from legumes). Scheffer and Schachtschabel (2010) p.402/403: normal input in Europe 1-30 kgN/ha/a, in tropics up to 100 kgN/ha/a. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

ORGANIC matter from animals: INTERPOLATE
Units: Ton/Year
This variable represents the total annual amount of organic matter application through animal manure. Because animal production is not endogenously represented in the model, this variable is taken from FAO data. Source: calculated from FAO. 2014. Food and Agriculture Organization. Emission Series. Faostat.org, accessed: 11 November 2014.

ORGANIC nitrogen from animals: INTERPOLATE
Units: Ton/Year
This variable represents organic nitrogen application on arable land through animal manure. Because animal production is not endogenously represented in the model, this variable is taken from FAO data. Source: calculated from FAO. 2014. Food and Agriculture Organization. Emission Series. Faostat.org, accessed: 11 November 2014.

Plant residue above ground dry matter = PLANT RESIDUE ABOVE GROUND INTERCEPT+PLANT RESIDUE ABOVE GROUND SLOPE*maize yield dry matter
Units: Ton/(Year*Ha)
This variable represents the amount of dry matter residues of maize production, above ground (excluding yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. Note: units conversion Mg = Mega grams = 10^6g = 1t.

Plant residue below ground dry matter = above ground dry matter*RATION BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production below ground (assumed that all organic matter is left in the soil as residues). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Page 11.14.

Plant residues remaining on the field = plant residue above ground dry matter*(1-share of above ground plant residues removed from the field)+plant residue below ground dry matter
Units: Ton/(Ha*Year)
This variable represents the total amount of plant residues remaining on the field (accounting for below-ground residues and above-ground-residues).

Relative soil organic matter = soil organic matter/INITIAL SOIL ORGANIC MATTER
Units: Dmnl
This variable represents the soil organic dry matter amount relative to its initial value.

Share of above ground plant residues removed from the field = IF THEN ELSE(Time<TIME OF SOIL ORGANIC MATTER POLICY IMPLEMENTATION, REFERENCE SHARE OF ABOVE GROUND PLANT RESIDUES REMOVED FORM THE FIELD, SHARE OF PLANT RESIDUES REMOVED UNDER SOIL ORGANIC MATTER POLICY)
Units: Dmnl
This variable represents the share of above ground plant residues that are removed from the field, ether for animal feeding, through burning or for other uses.

Soil Organic Carbon = INTEG (soil organic carbon input-soil organic carbon mineralization rate, INITIAL SOIL ORGANIC CARBON)
Units: Ton/Ha
Soil organic carbon is a major component of soil organic matter (SOM) and accumulates through the addition of biomass to the soil. Soil microbes and creatures decompose SOM through mineralization processes (Scheffer and Schachtschabel, 2010). SOM levels, and thus soil organic carbon levels, are low in Zambia (e.g. Tembo and Sitko, 2013). In the absence of time series, single measurements of soil organic carbon levels on arable land are available and indicate levels between 20 and 50 tons carbon per hectare (e.g. Kaonga and Coleman, 2008). This implies that the calibration check here is limited to a qualitative assessment. And since the levels are

and remain low during the reference period, the model is deemed adequate. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Tembo S., Sitko N. 2013. Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia; Kaonga M.L., Coleman K. 2008. Modeling soil organic carbon turnover in improved fallows in eastern Zambia using the RothC-26.3 model. Forest Ecology and Management, 256, (5), 1160-1166.

Soil organic carbon input = carbon in plant residues remaining on the field+animal carbon per hectare
Units: Ton/(Year*Ha)
This variable represents the addition of organic material to the soil (expressed in carbon units). Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production.

Soil organic carbon mineralization rate = Soil Organic Carbon/AVERAGE MINERALIZATION TIME
Units: Ton/(Year*Ha)
This variable represents the mineralization process of soil organic matter (SOM) and thus soil organic carbon. Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Soil organic matter = Soil Organic Carbon/CARBON SHARE IN DRY MATTER
Units: Ton/Ha
This variable represents the amount of organic dry matter in one hectare of arable land. "Soil organic matter (SOM) is probably the single component of the soil that has the greatest influence on the physical, chemical and biological properties of soils" (Shitumbanuma, 2013). SOM influences plant growth processes in manifold ways.

An important contribution happens through the mineralization of nutrients that are captured in SOM (Scheffer and Schachtschabel, 2010; and Schilling, 2000). And another important contribution is the improvement of soil structure, and soil nutrient, water and energy retention capacity. For adequately representing SOM I split SOM into two element components in this model (carbon and nitrogen). In Zambia SOM levels are low which results in low agricultural productivity (e.g. Tembo and Sitko, 2013). However, I did not find time series measuring SOM levels in Zambia (and most likely they do not exist). Sources: Shitumbanuma V., Chikuta F. 2013. Nutrient Status of the Major Agricultural Soils of the Eastern Province of Zambia, The International Institute of Tropical Agriculture: Lusaka, Zambia; Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Tembo S., Sitko N. 2013. Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Soil Organic Nitrogen = INTEG (NITROGEN FIXATION THROUGH SOIL BACTERIA+soil organic nitrogen input-soil organic nitrogen mineralization rate, INITIAL SOIL ORGANIC NITROGEN)
Units: Ton/Ha
Soil organic nitrogen is a major component of soil organic matter (SOM) and accumulates through the addition of biomass to the soil and soil bacteria fixating nitrogen from the air. Soil microbes and creatures decompose SOM through mineralization processes (Scheffer and Schachtschabel, 2010). Soil organic nitrogen that is mineralized serves as a nutrient for plant production (Schilling 2000). SOM levels, and thus soil organic nitrogen levels, are low in Zambia (e.g. Tembo and Sitko, 2013). In the absence of time series, single measurements of soil organic nitrogen levels are available and indicate levels between 1.5 and 2 tons carbon per hectare (e.g. https://daac.ornl.gov). This implies that the calibration check here is limited to a qualitative assessment. And since the levels are and remain low during the reference period, the model is deemed adequate. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum

Akademischer Verlag, Springer: Heidelberg, Germany; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Tembo S., Sitko N. 2013 Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Soil organic nitrogen input = animal organic nitrogen per hectare+total nitrogen in plant residues left on the field
Units: Ton/(Ha*Year)
This variable represents the addition of organic material to the soil (expressed in nitrogen units). Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production.

Soil organic nitrogen mineralization rate = Soil Organic Nitrogen/AVERAGE MINERALIZATION TIME
Units: Ton/(Year*Ha)
This variable represents the mineralization process of soil organic matter (SOM) and thus soil organic nitrogen. Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Total nitrogen in plant residues left on the field = nitrogen in plant residues below ground+nitrogen in plant residues above ground*(1-share of above ground plant residues removed from the field)
Units: Ton/(Year*Ha)
This variable represents the amount of nitrogen in plant residues left on the field after harvest.

A.3.3 Land Sector

Agricultural population = IF THEN ELSE(Time<2020, TOTAL economically active population in agriculture, TOTAL population*SHARE OF TOTAL POPULATION

IN AGRICULTURE)
Units: Person
This variable represents the total population working in agriculture. From 1984 to 2020 FAO data and estimations were available and applied. From 2021 to 2050 past trends were extrapolated to the future by multiplying the total population with the average historical share of people working in agriculture. Source: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

Arable Land = INTEG (arable land conversion rate-other land conversion rate, INITIAL ARABLE LAND AND PERMANENT CROPS)
Units: Ha
This stock represents the value of arable land (that is used for vegetal production, except grass). In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to settlement land. Source of reference data: calculated from FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

ARABLE LAND AND PERMANENT CROPS 1984 = 2.332e+006
Units: Ha
This constant is used to initialize land stocks and has no further dynamic implication. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Arable land conversion rate = MIN(desired arable land adjustment, Potential Arable Land/TIME TO DEVELOP ARABLE LAND)
Units: Ha/Year
This variable represents the net change from potential arable land into arable land. In the case of Zambia, land is abundant and the population is growing rapidly. Under

these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed).

Arable land demand = Arable Land+Arable Land*plant energy gap
Units: Ha
This variable defines the demand for arable land by adjusting the current land demand to the food security status of the population. If there is a food surplus, arable land decreases. And if there is food scarcity, arable land demand increases. This variable is the driver of land use change in the model and is founded in de Vries B. 2012. Sustainability Science. Cambridge University Press: Cambridge, UK.

Area harvested maize = Arable Land*share of maize on total area harvested
Units: Ha
This variable represents the area on which maize is produced. Note that one could differentiate between the area planted with maize and the area harvested with maize, etc. For simplicity I assume that they are equal and call it "area harvested maize" (to make it clear that this area is relevant for calculating the maize production).

Area harvested non maize = Arable Land-area harvested maize
Units: Ha
This variable represents the area on which other plants than maize are produced (excluding grass lands such as pastures and meadows).

AVERAGE DIETARY ENERGY REQUIREMENT = 2200
Units: Kcal/(Person*Day)
This constant represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organization of the United Nations (FAO) that calculate this parameter dependent on several population characteristics (e.g. age structure, level of physical activity, etc.). While the FAO value slightly changes over time, for simplicity, I assume a constant value of 2200 being realistic for the case of Zambia.

AVERAGE OTHER LAND PER PERSON = 0.1
Units: Ha/Person
This constant represents the area of other land that is needed per capita (for roads, settlements, etc.). Source: calculated from FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Average plant energy requirement = AVERAGE DIETARY ENERGY REQUIREMENT*SHARE OF PLANT CALORIES ON TOTAL DIET
Units: Kcal/(Person*Day)
This variable calculates the amount of calories in the Zambian diet that was covered from plant sources. It is exclusively based on past data and does not include any health recommendations.

Consumption vegetal products = per capita plant consumption kcal per year/DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the number of kilocalories from vegetal products that are on average consumed per person per day (excluding calories from animal sources). Reference data is taken from FAO (2014). Simulation results compared to historical data seem to fit badly at the first glance. However, the FAO data series for vegetal products consumptions has major flaws, at least for the single most important food item “maize”. When the FAO data is put in a dynamic context and inventory levels are calculated, the data suggests that at a point in time the maize inventory level reaches five times the quantity of a normal annual maize harvest. Thus, while the inventories seem to overflow, people simultaneously suffer from hunger. This is unrealistic. Therefore the divergence of simulation results compared to data is acceptable and other, more reliable variables such as yield, production and land allocation are better suited for calibration. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

COUNTRY area: INTERPOLATE
Units: Ha
This variable is used to initialize land stocks and has no further dynamic implication. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Desired arable land adjustment = (realistic land demand-Arable Land)/TIME TO DEVELOP ARABLE LAND+other land conversion rate
Units: Ha/Year
This variable represents desired adjustment of arable land.

Desired other land = TOTAL population*AVERAGE OTHER LAND PER PERSON
Units: Ha
This variable represents the desired area of other land (such as roads, settlement area, etc.).

EFFECT OF PROFIT ON MAIZE AREA SHARE INTERCEPT = 0.2
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to allocate land to maize production. It was estimated using indirect optimization.

EFFECT OF PROFIT ON MAIZE AREA SHARE SLOPE = 0.5
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to allocate land to maize production. It was estimated using indirect optimization.

ESTIMATE YIELD NON MAIZE 2012 = 5.5e+006
Units: Kcal/(Year*Ha)
This variable is used to formulate the future scenario for "yield non maize" and prescribes past trends.

Estimate yield non maize 2050 = ESTIMATE YIELD NON MAIZE 2012+YIELD NON MAIZE CHANGE 2012 TO 2050

Units: Kcal/(Year*Ha)
This variable is used to formulate the exogenous scenario for "yield non maize".

INITIAL ARABLE LAND AND PERMANENT CROPS = INITIAL(MIN(ARABLE LAND AND PERMANENT CROPS 1984+INITIAL SHIFT OF ARABLE LAND-SHORT term meadows, maximal area under cultivation))
Units: Ha
This variable is used to initialize land stocks and has no further dynamic implication.
Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

INITIAL OTHER LAND = INITIAL(700000)
Units: Ha
This variable is used to initialize land stocks and has no further dynamic implication.
Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

INITIAL POTENTIAL ARABLE LAND = INITIAL(COUNTRY area-INITIAL ARABLE LAND AND PERMANENT CROPS-INLAND water-INITIAL OTHER LAND)
Units: Ha
This variable is used to initialize land stocks and has no further dynamic implication.
Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

INITIAL SHIFT OF ARABLE LAND = 100000
Units: Ha
This variable is used to initialize land stocks and has no further dynamic implication.
Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

INLAND water: INTERPOLATE
Units: Ha

This variable is used to initialize land stocks and has no further dynamic implication. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Maximal area under cultivation = agricultural population*MAXIMUM CULTIVATION AREA PER PERSON
Units: Ha
This variable represents the maximum area that can be cultivated given the current agricultural workforce and its productiveness.

MAXIMUM CULTIVATION AREA PER PERSON = 0.5
Units: Ha/Person
This variable represents the maximum productiveness of an agricultural workforce in terms of area coverage. The productiveness is restricted by low endowment. A value around 0.5 hectares per person per year is realistic (Personal message from Dr. P. Nyanga, University of Zambia, Lusaka).

Non maize production = area harvested non maize*yield non maize
Units: Kcal/Year
This variable represents the production of plant products other than maize.

Other Land = INTEG (other land conversion rate, INITIAL OTHER LAND)
Units: Ha
This stock represents the value of other land (such as settlements, roads, etc.). Source of reference data: calculated from FAO (2014). Potentially, an area could move fourth and back from one to another land category. In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to settlement land. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Other land conversion rate = MAX(0, MIN(other land gap/TIME TO DEVELOP OTHER LAND, Arable Land/TIME TO DEVELOP OTHER LAND))
Units: Ha/Year
This variable represents the change between other land and arable land. In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to settlement land.

Other land gap = desired other land-Other Land
Units: Ha
This variable represents the difference between desired amount of other land and the actual amount of other land (other land includes roads, settlements, etc.).

Plant energy gap = (average plant energy requirement-consumption vegetal products)/consumption vegetal products
Units: Dmnl
This variable calculates the relative gap of plant energy consumption. If the plant energy consumption equals the required quantity, there is no gap and the variable takes on the value 0. If there is less plant food than required, this variable takes on a value >1 and if there is more pant food than required, this variable takes on a value<1. This variable drives land use change and is founded in de Vries B. 2012. Sustainability Science. Cambridge University Press: Cambridge, UK.

Potential Arable Land = INTEG (-arable land conversion rate, INITIAL POTENTIAL ARABLE LAND)
Units: Ha
This stock represents the level of potential arable land including forest, savannah, pastures and permanent meadows. Source of reference data: calculated from FAO (2014). In the case of Zambia, land is abundant and the population is growing rapidly. Under these conditions and for simplicity, I assume that land is just transformed from potential arable land to arable land (and back if needed), and from arable land to

settlement land. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Realistic land demand = MIN(arable land demand, maximal area under cultivation)
Units: Ha
This variable represents the final (realistic) arable land demand eventually corrected for productivity restrictions.

Relative perceived gross profit per hectare maize = Perceived Gross Profit Per Hectare Maize/INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE
Units: Dmnl
This variable represents the perceived per area gross profit indicator of maize production relative to its initial value.

Share of maize on total area harvested = MIN(EFFECT OF PROFIT ON MAIZE AREA SHARE INTERCEPT+relative perceived gross profit per hectare maize*EFFECT OF PROFIT ON MAIZE AREA SHARE SLOPE,1)
Units: Dmnl
This variable represents share of arable land being allocated to maize production. Similar to the "average value product" concept in Stephens et al. (2012) I use a profit indicator to determine the allocation of land. Source: Stephens E. C., Nicholson C. F., Brown D. R., Parsons D., Barrett C. B., Lehmann J., Mbugua D., Ngoze S., Pell A. N. & Riha S. J. 2012. Modeling the impact of natural resource-based poverty traps on food security in Kenya: The Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model. Food Security, 4, 423–439.

SHARE OF PLANT CALORIES ON TOTAL DIET = 0.94
Units: Dmnl
This constant represents the share of kilocalories coming from plants compared to the total diet. It is estimated from: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

SHARE OF TOTAL POPULATION IN AGRICULTURE = 0.241753

Units: Dmnl

This constant represents the share of people economically active in agriculture relative to the total population. The value was estimated from a data set from Zambia: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

SHORT term meadows: INTERPOLATE

Units: Ha

This variable is used to initialize land stocks and has no further dynamic implication. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

TIME TO DEVELOP ARABLE LAND = 4

Units: Year

This constant represents the time it takes to convert forest, savannah and permanent meadows into arable land.

TIME TO DEVELOP OTHER LAND = 2

Units: Year

This variable represents time it takes to convert arable land into other land.

TOTAL economically active population in agriculture: INTERPOLATE

Units: Person

This variable represents the population that is economically active in agriculture and is a subpart of the total population. It is an exogenous model input and data / scenario is available from 1984 to 2020. Source: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

TOTAL population: INTERPOLATE

Units: Person

This variable represents the total population. Total population is an exogenous input to the model and both - data for the past and the scenario for the future - are taken from FAO (2014). Malthusian theory states that the population level is dependent on food availability. By using population as an exogenous model input I do not want to challenge this theory. Such a link from food availability to population could potentially be implemented in the model (and was tested). However, population also depends on other determinants that are not represented in the model (physical and socio-economic phenomena). By implementing just the single link from food availability to population I would pretend a population study based on weak theory and the study would loose its focus on food production system. Thus, I exclude this link and analyze how the system reacts to the exogenous input. Data source: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

YEAR 2012 = 2012
Units: Year
Year 2012.

YEAR 2050 = 2050
Units: Year
Year 2050.

Yield non maize = IF THEN ELSE(Time<2012, YIELD non maize data, yield non maize 2012 to 2050)
Units: Kcal/(Year*Ha)
This variable represents the average yield of non-maize plants. It embraces both, changes in relative importance among different plant products, as well as changes of yields within the same plant product. Because study focuses on maize, this non-maize yield is derived from external data.

Yield non maize 2012 to 2050 = ESTIMATE YIELD NON MAIZE 2012+(estimate yield non maize 2050-ESTIMATE YIELD NON MAIZE 2012)/(YEAR 2050-YEAR 2012)*(Time-YEAR 2012)

Units: Kcal/(Year*Ha)

This variable is used to formulate the exogenous scenario for "yield non maize".

YIELD NON MAIZE CHANGE 2012 TO 2050 = 1e+006

Units: Kcal/(Year*Ha)

This variable is used to formulate the exogenous scenario for "yield non maize".

YIELD non maize data: INTERPOLATE

Units: Kcal/(Year*Ha)

This variable represents the past yield development of pant products other than maize in kilocalories. It is calculated from: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014; and FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

A.3.4 Supply and Demand Sector

Area harvested maize = Arable Land*share of maize on total area harvested

Units: Ha

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

AVERAGE DIETARY ENERGY REQUIREMENT = 2200

Units: Kcal/(Person*Day)

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

AVERAGE FOOD RESERVE SUBSIDY REAL 1984 TO 2011 = 1.49654e+010
Units: Rlc/Year
This constant builds the future scenario of food reserve subsidies and is derived by calculating the average over the reference period up to 2009 (including the 1990s without subsidies).

AVERAGE VALUE ADDED 1984 TO 2009 = 93
Units: Rlc/Kg
This variable represents a future scenario for the value added along the maize value chain (in real local currency per kilogram of maize). It was obtained by calculating the average value of the reference period.

Change in perceived supply demand balance = (supply demand balance-Perceived Supply Demand Balance)/TIME TO PERCEIVE SUPPLY DEMAND BALANCE
Units: Dmnl/Year
This variable represents change of the perception of the ratio between potentially supplied and demanded quantity of maize.

Consumer price maize = producer price maize real+value added- subsidy per kg
Units: Rlc/Kg
This variable represents the consumer price of maize (in real local currency per kilogram of maize). It is derived from the producer price by adding the value added (value added from subsequent actors in the value chain, including their costs) and subtracting reserve subsidies.

Consumer price maize per ton = consumer price maize*KG PER TON
Units: Rlc/Ton
This variable represents the consumer price of maize (in real local currency per ton of maize).

DAYS PER YEAR = 365
Units: Day/Year
This constant represents the number of days per year (365).

Demand curve shift = indicated total maize consumption-REFERENCE FOOD MAIZE DEMAND
Units: Ton/Year
This variable represents shifts in maize demand due to a change in total population.

Demand curve slope = ELASTICITY REFERENCE INDUSTRY DEMAND*REFERENCE FOOD MAIZE DEMAND/REFERENCE CONSUMER PRICE MAIZE PER TON
Units: Ton*Ton/(Rlc*Year)
This variable represents the maize demand curve slope. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

Domestic maize consumption = MIN(domestic maize demand, potential domestic maize supply)
Units: Ton/Year
This variable represents the realized annual domestic maize consumption that is withdrawn from the inventories. If demand is higher than potential supply, this variable equals potential supply. And if potential supply is higher than demand, this variable equals demand.

Domestic maize demand = food maize demand+maize for non food use
Units: Ton/Year
This variable represents the total annual maize demand including food and non-food.

Effect of supply and demand on producer price = relative supply demand balance^SENSITIVITY OF PRICE TO SUPPLY DEMAND BALANCE
Units: Dmnl
This variable calculates the effect of a change in the perceived supply-demand ratio on the indicated producer price of maize. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

ELASTICITY REFERENCE INDUSTRY DEMAND = -0.1

Units: Dmnl

This variable indicates the price-quantity relationship on the maize demand curve. Since maize is the staple crop and plays a central role in the diet it is assumed to be inelastic. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

ENERGY share of maize on total diet: INTERPOLATE

Units: Dmnl

This variable represents the past share of kilocalories coming from maize compared to the total diet. The past trajectory was calculated from FAO, and the last value is applied as future scenario. Source: calculated from FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

EXPORT maize: INTERPOLATE

Units: Ton/Year

This variable represents the past development of maize exports of Zambia. Because trade is represented exogenously (due to its politically driven unpredictability), this variable is taken from FAO data. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

EXPORT MAIZE SCENARIO AFTER 2011 = 0

Units: Ton/Year

This constant represents the future scenario for how much maize is exported from Zambia. The value is set to zero. The reason is an assumed goal of food self-sufficiency. It is clear that maize trade is an option for Zambia and most likely will happen in the future. However, from an endogenous point of view, it is interesting to study the dynamics internal to the food production system. Therefore, and because food trade is politically motivated and difficult to foresee, the value of zero is applied. Scenario analysis revealed that the main study results are robust under different development patterns.

FLOOR price namboard and food reserve agency real: INTERPOLATE
Units: Rlc/Kg
The government of the republic of Zambia sometimes intervenes into the maize market by buying maize. The politically determined price has the role of a floor price and thus defines a lower limit for the producer price of maize. The price was implemented through NAMBOARD and the Food Reserve Agency (FRA) that were/are parastatal organizations. Data sources: Kumar S.K. 1988. Design, Income Distribution, and Consumption Effects of Maize Pricing Policies in Zambia. In Food Subsidies in Developing Countries, Published for International Food Policy Research Institute. Johns Hopkins University Press: Baltimore, USA, 1988, pp 289 – 300; Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA; Mason N.M., Myers R.J. 2013. The effects of the Food Reserve Agency on maize market prices in Zambia. Agricultural Economics, 44, (2), 203-216.

Food maize demand = MAX(0, REFERENCE FOOD MAIZE DEMAND+demand curve shift-demand curve slope*REFERENCE CONSUMER PRICE MAIZE PER TON+demand curve slope*consumer price maize per ton)
Units: Ton/Year
This variable represents the annual maize demand for food purposes. Henrichsmeyer and Witzke (1991) list three main factors determining food demand on an aggregated long-term level: population development, food prices and income. Here, maize demand depends on the population's needs and the consumer price. Income is assumed to have a constant effect and is omitted, because the population effect is much bigger in fast growing populations (Henrichsmeyer and Witzke 1991). Conceptually this variable is based in Sterman (2000). Sources: Henrichsmeyer W., Witzke H.P. 1991. Agrarpolitik Band 1 Agrarökonomische Grundlagen; Eugen Ulmer GmbH & Co.: Stuttgart, Germany; Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

IMPORT maize: INTERPOLATE
Units: Ton/Year

This variable represents the past development of the amount of maize imported to Zambia. Because trade is represented exogenously (due to its politically driven unpredictability), this variable is taken from FAO data. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

IMPORT MAIZE SCENARIO AFTER 2011 = 0
Units: Ton/Year
This constant represents the future scenario for how much maize is imported to Zambia. The value is set to zero. The reason is an assumed goal of food self-sufficiency. It is clear that maize trade is an option for Zambia and most likely will happen in the future. However, from an endogenous point of view, it is interesting to study the dynamics internal to the food production system. Therefore, and because food trade is politically motivated and difficult to foresee, the value of zero is applied. Scenario analysis revealed that the main study results are robust under different development patterns.

Indicated producer price maize = effect of supply and demand on producer price*REFERENCE PRODUCER PRICE MAIZE REAL
Units: Rlc/Kg
This variable represents the indicated producer price for maize according to market forces (supply-demand-balance) and is conceptually founded in microeconomic theory (e.g. Varian, 2007.). This variable equals the effective producer price for maize in the absence of an FRA/namboard price or if it is higher than those. Source: Varian H.R. 2007. Grundzüge der Mikroökonomik. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

Indicated total calory consumption = TOTAL population*AVERAGE DIETARY ENERGY REQUIREMENT*DAYS PER YEAR
Units: Kcal/Year
This variable represents the indicated annual total food consumption of the total population in kilocalories.

Indicated total maize consumption = indicated total calory consumption*ENERGY share of maize on total diet/(KCAL PER KG MAIZE*KG PER TON)
Units: Ton/Year
This variable represents the indicated total annual maize consumption for food purposes in tons.

INITIAL MAIZE INVENTORY = 0
Units: Ton
This variable represents the initial value of the maize inventory stock. Because the model addresses long-term phenomena, we are interested in the long-term development of the maize inventory (instead of seasonal changes). Thus, the inventory stock captures the level just before the new maize harvest. The “normal” level is therefore zero.

INVENTORY HANDLING TIME = 1
Units: Year
This constant represents the average inventory handling time.

KCAL PER KG MAIZE = 3071
Units: Kcal/Kg
This constant represents the number of kilocalories per kilogram maize. It is estimated from FAO data. Source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

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

Maize for non food use = maize for seed use+(SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER+SHARE OF MAIZE PRODUCTION WASTE)*potential domestic maize supply
Units: Ton/Year

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

Maize for seed use = area harvested maize*SEED PER HECTARE
Units: Ton/Year
This variable represents the annual amount of maize used as seeds for planting the fields.

Maize Inventory = INTEG (maize production+net import maize-domestic maize consumption, INITIAL MAIZE INVENTORY)
Units: Ton
Unlike in classic microeconomic theory, this model allows for dis-equilibrium. If the demand is smaller than potential supply, surplus maize is stored in the inventory. Because the model addresses long-term phenomena, we are interested in the long-term development of the maize inventory (instead of seasonal changes). Thus, the present inventory stock captures the level just before the new maize harvest. The "normal" level is therefore zero. Only after years with surpluses the inventory starts to build up in this model. Conceptually the stock variable is taken from Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Maize production = area harvested maize*maize yield
Units: Ton/Year
This variable represents the total annual domestic maize production. Maize production is a suitable calibration variable because of the reliability of its reference data and due to its central role in the model (it is part of many feedback loops). Reference data source: FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

Maize yield = YIELD PLATEAU*effect of nitrogen on yield*effect of water on yield
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize grain harvested on one hectare, some water remains in the grain). It is calculated using a Mitscherlich-

Baule production function (Schilling 2000). For choosing a production function, many alternatives are potentially available (e.g. square root functions, linear min-function, polynomic functions etc.). I chose a Mitscherlich-Baule production function because it is applicable on a large geographical and temporal scale, allows for factor substitution, has empirical support and is adequate in complexity compared with the rest of the model. Because factor endowment is low in Zambia, a stage II function is acceptable (compared to a stage III function). Unlike as in the common approach, I calculate yield based on realized element uptake instead of application rates to be operational. Maize yield is a suitable variable for comparing simulation results with historical data, because yield is part of many feedback loops and historical data is reliable (FAO data was used for calibration and it was triangulated with other sources; FAO 2014). Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

Net import maize = IF THEN ELSE(Time<2012, IMPORT maize-EXPORT maize,IMPORT MAIZE SCENARIO AFTER 2011-EXPORT MAIZE SCENARIO AFTER 2011)
Units: Ton/Year
This variable calculates the net import of maize to Zambia (net import = import - export).

Perceived Supply Demand Balance = INTEG (change in perceived supply demand balance, REFERENCE SUPPLY DEMAND BALANCE)
Units: Dmnl
This stock represents the perception of the ratio between potentially supplied and demanded quantity of maize. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

Potential domestic maize supply = maize production+net import maize+Maize Inventory/INVENTORY HANDLING TIME
Units: Ton/Year

This variable represents the maize quantity that can be maximally supplied to the market. It includes the current production as well as production from previous years that are stored in maize inventories. Conceptually it is taken from Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Producer price maize real = IF THEN ELSE(Time<2011, MAX(indicated producer price maize, FLOOR price namboard and food reserve agency real), indicated producer price maize)
Units: Rlc/Kg
This variable represents the producer price of maize (in real local currency per kilogram). For the reference period, the variable takes on the maximum value of the indicated producer price on the market and the floor price determined by the pubic Food Reserve Agency (FRA). For simulating the future, only the indicated producer price is applied because the FRA floor price follows is rather undeterminable (determined in a political process). Producer price is a variable part of many feedback loops. Still it was not used as a main variable for calibration since long-term data is scarce and from 1988 to 1995 even missing. Thus, the focus was on the main trend, however, not on the variations.

REFERENCE CONSUMER PRICE MAIZE = INITIAL(consumer price maize)
Units: Rlc/Kg
This variable represents the initial consumer price per kilogram of maize in real local currency.

REFERENCE CONSUMER PRICE MAIZE PER TON = INITIAL(REFERENCE CONSUMER PRICE MAIZE*KG PER TON)
Units: Rlc/Ton
This variable represents the initial consumer price per ton of maize in real local currency. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

REFERENCE FOOD MAIZE DEMAND = INITIAL(indicated total maize consumption)
Units: Ton/Year
This variable represents the annual reference maize demand in tons. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

REFERENCE PRODUCER PRICE MAIZE REAL = 55
Units: Rlc/Kg
This constant represents the reference producer price of maize that is realized when supply and demand are in balance (in real local currency per kilogram).

REFERENCE SUPPLY DEMAND BALANCE = 1
Units: Dmnl
This constant represents the initial, perceived level of the ratio between potentially supplied and demanded quantity of maize.

Relative supply demand balance = Perceived Supply Demand Balance/REFERENCE SUPPLY DEMAND BALANCE
Units: Dmnl
This variable represents the relative state of the perceived ratio between potentially supplied and demanded quantity of maize compared to its initial value.

Sales maize = maize production*share of maize production sold
Units: Ton/Year
This variable represents the annual amount of maize being sold at a market. In western countries this variable would typically be equal to the production. In the case of Zambia, maize is partly sold and partly self-consumed. Thus, this variable is only a share of the total production, and the producers consume the rest. Source: Chapoto A., Haggblade S., Hichaambwa M., Kabwe S., Longabaugh S., Sitko N., Tschirley, D. 2012. Agricultural Transformation in Zambia: Alternative Institutional Models for Accelerating Agricultural Productivity Growth and Commercialization, IAPRI: Lusaka, Zambia.

SEED PER HECTARE = 0.03

Units: Ton/(Ha*Year)

This constant represents the amount of maize seeds that are used to plant one average hectare. It was calculated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

SENSITIVITY OF PRICE TO SUPPLY DEMAND BALANCE = -0.86

Units: Dmnl

This constant represents how sensitive the producer price of maize reacts to changes in the perceived supply demand ratio. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER = 0.02

Units: Dmnl

This constant represents the share of total annual maize supply used to feed animals. It was calculated from FAO data (FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014).

SHARE OF MAIZE PRODUCTION WASTE = 0.033

Units: Dmnl

This constant represents the share of total annual maize supply being lost and wasted. It was calculated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Subsidy per kg = IF THEN ELSE(Time<2012, SUBSIDY per kg maize real, ZIDZ(AVERAGE FOOD RESERVE SUBSIDY REAL 1984 TO 2011,(KG PER TON*sales maize)))

Units: Rlc/Kg

The government of the republic of Zambia keeps maize reserves (through the Food Reserve Agency). The reserves are either sold at subsidized conditions to millers or the government has to cover losses from the reserve operations. This results in a lower difference between producer and consumer price for maize. Thus, the variable here represents this maize subsidy expressed on a kilogram basis. Sources: Kumar

S.K. 1988. Design, Income Distribution, and Consumption Effects of Maize Pricing Policies in Zambia. In Food Subsidies in Developing Countries, Published for International Food Policy Research Institute. Johns Hopkins University Press: Baltimore, USA, pp 289 – 300; GRZ. Various years. Estimates of Revenue and Expenditure (including Capital and Constitutional and Statutory Expenditure). GRZ, Lusaka, Zambia; Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA; Zulu B., Nijhoff J.J., Jayne T.S., Negassa A. 2000. Is the glass half-empty or half full? An analysis of agricultural production trends in Zambia. FSRP: Lusaka, Zambia; Chiwele D., Fowler M., Humphrey E., Hurrell A.,Willis J. 2010. Agriculture Case Study: Evaluation of Budget Support in Zambia. Oxford Policy Management; Howard J.A., Chitalu G.M., Kalonge S. M. 1993. The impact of investments in maize research and dissemination in Zambia part one: main report, Michigan State University: Michigan, USA.

SUBSIDY per kg maize real: INTERPOLATE
Units: Rlc/Kg
The government of the republic of Zambia keeps maize reserves (through the Food Reserve Agency). The reserves are either sold at subsidized conditions to millers or the government has to cover losses from the reserve operations. This results in a lower difference between producer and consumer price for maize. Thus, the variable here represents this maize subsidy expressed on a kilogram basis. Sources: Kumar S.K. 1988. Design, Income Distribution, and Consumption Effects of Maize Pricing Policies in Zambia. In Food Subsidies in Developing Countries, Published for International Food Policy Research Institute. Johns Hopkins University Press: Baltimore, USA, pp 289 – 300; GRZ. Various years. Estimates of Revenue and Expenditure (including Capital and Constitutional and Statutory Expenditure). GRZ, Lusaka, Zambia; Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA; Zulu B., Nijhoff J.J., Jayne T.S., Negassa A. 2000. Is the glass half-empty or half full? An analysis of agricultural production trends in Zambia. FSRP: Lusaka, Zambia; Chiwele D., Fowler M., Humphrey E., Hurrell A.,Willis J.

2010. Agriculture Case Study: Evaluation of Budget Support in Zambia. Oxford Policy Management; Howard J.A., Chitalu G.M., Kalonge S. M. 1993. The impact of investments in maize research and dissemination in Zambia part one: main report, Michigan State University: Michigan, USA.

Supply demand balance = potential domestic maize supply/domestic maize demand
Units: Dmnl
This variable represents the ratio between potentially supplied and demanded quantity of maize. Unlike in classic microeconomic theory, this model allows for dis-equilibrium. If the market is equilibrated and supply equals demand, then this variable takes on the value of 1. Otherwise it increases above or falls below 1. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

TIME TO PERCEIVE SUPPLY DEMAND BALANCE = 0.3
Units: Year
This variable represents the time it takes to perceive changes in the ratio between potentially supplied and demanded quantity of maize.

TOTAL population: INTERPOLATE
Units: Person
This variable represents the total population. Total population is an exogenous input to the model and both - data for the past and the scenario for the future - are taken from FAO (2014). Malthusian theory states that the population level is dependent on food availability. By using population as an exogenous model input I do not want to challenge this theory. Such a link from food availability to population could potentially be implemented in the model (and was tested). However, population also depends on other determinants that are not represented in the model (physical and socio-economic phenomena). By implementing just the single link from food availability to population I would pretend a population study based on weak theory and the study would loose its focus on food production system. Thus, I exclude this link and analyze how the system reacts to the exogenous input. Data source: FAO.

2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

Value added = IF THEN ELSE(Time<2010, VALUE added real, AVERAGE VALUE ADDED 1984 TO 2009)
Units: Rlc/Kg
This variable represents the value added along the maize value chain plus the margins (resulting in the difference between producer and consumer price, expressed in real local currency per kilogram of maize).

VALUE added real: INTERPOLATE
Units: Rlc/Kg
This variable represents the value added along the maize value chain plus the margins (resulting in the difference between producer and consumer price, expressed in real local currency per kilogram of maize). It is obtained and calculated from various sources. Among others: Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA.

A.3.5 Farm Decisions Sector

Aggregated Farm Income Maize Real = INTEG (change of aggregated farm income maize, INITIAL AVERAGE FARM INCOME MAIZE)
Units: Rlc/Year
This stock represents the annual aggregate farm sector income trough maize sales (being disposable after one year to buy inputs for the following growing season, in real local currency: Kwacha94). For completeness one could represent here the whole income of Zambian smallholder farmers instead of just the income from maize. However, then these sources of income should be modeled endogenously, or the additional income would be derived from data. The first case would shift the focus from fertilizer subsidy programs and maize production towards a macroeconomic model, and the second case would just introduce another source of external influence.

Because the aim of this model is to study the maize production system from a endogenous perspective, I focus on the endogenous part of the income (income from maize sales) and leave other source away. Aggregated Farm Income Maize Real is modeled as an information stock under the assumption that all the maize income is spent throughout the year and no cash accumulation happens. The assumption is reasonable in the low endowment setting of smallholder farmers in Zambia.

Area harvested maize = Arable Land*share of maize on total area harvested
Units: Ha
This variable represents the area on which maize is produced. Note that one could differentiate between the area planted with maize and the area harvested with maize, etc. For simplicity I assume that they are equal and call it “area harvested maize” (to make it clear that this area is relevant for calculating the maize production).

AVERAGE SHARE OF FARM INCOME MAIZE TO FERTILIZER 1984 TO 2009 = 0.57
Units: Dmnl
This constant is used to build the future scenario of the share of income that farmers spend on fertilizer purchases. It equals the average value of the reference period.

Change in perceived gross profit per hectare maize = (gross profit per hectare maize-Perceived Gross Profit Per Hectare Maize)/TIME TO PERCEIVE PER HECTARE MAIZE GROSS PROFIT
Units: Rlc/(Year*Year*Ha)
This variable represents the change in perceived per area gross profit indicator of maize production.

Change in perceived pc food maize supply = (consumption maize products-Perceived Food Supply Maize)/TIME TO PERCEIVE FOOD MAIZE SUPPLY
Units: Kcal/(Person*Day*Year)
This variable represents the change in farmers’ perception of maize supply.

Change of aggregated farm income maize = (farm income maize real-Aggregated Farm Income Maize Real)/TIME TO ADJUST FARM INCOME MAIZE
Units: Rlc/(Year*Year)
This variable represents the change in aggregated maize income.

Consumption maize products = per capita food maize consumption kcal per year/DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the number of total kilocalories from maize products that are consumed per person per day. It is a key indicator for measuring the food production system's performance. Reference data is taken from FAO (2014). Simulation results compared to historical data seem to fit badly at the first glance. However, the FAO data series for maize consumptions has major flaws. When data is put in a dynamic context and inventory levels are calculated, the data suggests that at a point in time the maize inventory level reaches five times the quantity of a normal annual maize harvest. Thus, while the maize inventories seem to overflow, people simultaneously suffer from hunger. This is unrealistic. Therefore the divergence of simulation results compared to data is acceptable and other, more reliable variables such as yield, production and land allocation are better suited for calibration. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

CONTINUOUS FERTILIZER SUBSIDY REDUCTION SWITCH = 0
Units: Dmnl
This constant activates or deactivates the linear decrease in fertilizer subsidy program expenditures. If the constant is set to value 1, the decrease happens (in experiment 8), if the constant is set to the value 0 the decrease does not happen (in experiments 1-7).

Continuous reduction = -RAMP(FERTILIZER SUBSIDY FUTURE/(END TIME CONTINOUS REDUCTION-START TIME CONTINOUS REDUCTION), START TIME CONTINOUS REDUCTION,END TIME CONTINOUS REDUCTION)
Units: Rlc/Year

This variable is only used in experiment 8 (see paper) and calculates the linear decrease in fertilizer subsidy program expenditures.

EFFECT OF FOOD SUPPLY MAIZE ON SHARE SOLD INTERCEPT = 0.055
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to sell maize depending on perceived maize availability. It was estimated using indirect optimization.

EFFECT OF FOOD SUPPLY MAIZE ON SHARE SOLD SLOPE = 0.44
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to sell maize depending on perceived maize availability. It was estimated using indirect optimization.

EFFECT OF GROSS PROFIT ON SHARE SOLD INTERCEPT = 0.0862
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to sell maize depending on perceived maize gross profitability. It was estimated using indirect optimization.

EFFECT OF GROSS PROFIT ON SHARE SOLD SLOPE = 0.328164
Units: Dmnl
This constant is a parameter used to represent the farmers' decision to sell maize depending on perceived maize gross profitability. It was estimated using indirect optimization.

END TIME CONTINOUS REDUCTION = 2040
Units: Year
This constant is only used in experiment 8 (see paper) and determines when the fertilizer subsidy program completely expires.

Expenditure fertilizer subsidy program = IF THEN ELSE(Time<2012, PUBLIC expenditure for fertilizer subsidies, FERTILIZER SUBSIDY FUTURE-fertilizer

subsidy drop*SWITCH FERTILIZER SUBSIDY DROP)+continuous reduction*CONTINUOUS FERTILIZER SUBSIDY REDUCTION SWITCH
Units: Rlc/Year
This variable combines past development and future scenario for the expenditure of the fertilizer subsidy program. It is expressed in real local currency (Kwacha94).

Farm income maize real = producer price maize real*sales maize*KG PER TON
Units: Rlc/Year
This variable represents the annual aggregate farm income received trough the sales of maize (in real local currency: Zambian Kwacha94). The multiplication of quantity and price is based in microeconomic theory: E.g. Varian (2007). Source: Varian H.R. 2007. Grundzüge der Mikroökonomik. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

Fertilizer subsidy drop = STEP(FERTILIZER SUBSIDY FUTURE, FERTILIZER SUBSIDY DROP TIME)
Units: Rlc/Year
This variable initiates the drop of fertilizer subsidies in experiment 3, 5 and 7.

FERTILIZER SUBSIDY DROP TIME = 2030
Units: Year
This constant determines the time point, when fertilizer subsidies are removed in experiments 3, 5 and 7.

FERTILIZER SUBSIDY FUTURE = 1.89203e+010
Units: Rlc/Year
This constant defines the future expenditure for the fertilizer subsidy program. It is varied from one experiment to another depending on the policy assumption (see Article 1).

Gross profit per hectare maize = per hectare maize income-per hectare fertilizer expenditure
Units: Rlc/(Year*Ha)

This variable represents a per area gross profit indicator of maize production. It uses the most important source of revenue and the largest single cost as a base for calculation. Source: Burke W.J., Hichaambwa M., Banda D., Jayne T.S. 2011. The Cost of Maize Production by Smallholder Farmers in Zambia, Food Security Research Project: Lusaka, Zambia.

Indicated share of production sold from maize availability = EFFECT OF FOOD SUPPLY MAIZE ON SHARE SOLD INTERCEPT+EFFECT OF FOOD SUPPLY MAIZE ON SHARE SOLD SLOPE*relative perceived food maize supply
Units: Dmnl
This variable represents the farmers' decision to sell maize depending on perceived maize supply. It is assumed to follow a positive linear relationship, meaning the more maize is available the more are farmers willing to sell (e.g. a surplus). If maize is scarce farmers are assumed to be less willing to sell maize.

Indicated share of production sold from maize gross profit = relative perceived gross profit per hectare maize*EFFECT OF GROSS PROFIT ON SHARE SOLD SLOPE+EFFECT OF GROSS PROFIT ON SHARE SOLD INTERCEPT
Units: Dmnl
This variable represents the farmers' decision to sell maize depending on perceived maize gross profitability. It is assumed to follow a positive linear relationship, meaning the more maize is profitable, the more farmers are willing to sell. If maize is less profitable, farmers are assumed to be less willing to sell maize.

INITIAL AVERAGE FARM INCOME MAIZE = 6.69569e+010
Units: Rlc/Year
This constant represents the initial annual aggregated farm income from maize (in real local currency: Kwacha94).

INITIAL PERCEIVED FOOD SUPPLY MAIZE = 1278
Units: Kcal/(Person*Day)
This variable represents initial farmers' perception of maize supply.

INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE = INITIAL(176414)
Units: Rlc/(Year*Ha)
This variable represents the initial level of the perceived per area gross profit indicator of maize production.

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

Maize production = area harvested maize*maize yield
Units: Ton/Year
This variable represents the total annual domestic maize production. Maize production is a suitable calibration variable because of the reliability of its reference data and due to its central role in the model (it is part of many feedback loops). Reference data source: FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

Maize yield = YIELD PLATEAU*effect of nitrogen on yield*effect of water on yield
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize grain harvested on one hectare, some water remains in the grain). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). For choosing a production function, many alternatives are potentially available (e.g. square root functions, linear min-function, polynomic functions etc.). I chose a Mitscherlich-Baule production function because it is applicable on a large geographical and temporal scale, allows for factor substitution, has empirical support and is adequate in complexity compared with the rest of the model. Because factor endowment is low in Zambia, a stage II function is acceptable (compared to a stage III function). Unlike as in the common approach, I calculate yield based on realized element uptake instead of application rates to be operational. Maize yield is a suitable variable for comparing simulation results with historical data, because yield is part of many feedback loops and historical data is

reliable (FAO data was used for calibration and it was triangulated with other sources; FAO 2014). Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

NITROGEN fertilizer price real data: INTERPOLATE
Units: Rlc/Kg
This variable represents the past development of nitrogen fertilizer prices (in real local currency: Zambian Kwacha 94). Because fertilizers include various combinations of nutrition elements, this price is calculated. Source: MAOC. Various years. Provincial Prices from 1994 to 2012. Ministry of Agriculture and Cooperatives, Lusaka, Zambia.

Per hectare fertilizer expenditure = private fertilizer expenditure/area harvested maize
Units: Rlc/(Year*Ha)
This variable represents the annual per hectare fertilizer expenditure of farmers (excluding subsidies).

Per hectare maize income = maize yield*producer price maize real*KG PER TON
Units: Rlc/(Year*Ha)
This variable represents the potential annual per hectare maize income by farmers. See: Varian H.R. 2007. Grundzüge der Mikroökonomik. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

Perceived Food Supply Maize = INTEG (change in perceived pc food maize supply, INITIAL PERCEIVED FOOD SUPPLY MAIZE)
Units: Kcal/(Person*Day)
This variable represents the initial per capita maize supply situation perceived by farmers.

Perceived Gross Profit Per Hectare Maize = INTEG (change in perceived gross profit per hectare maize, INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE)

Units: Rlc/(Year*Ha)

This stock represents the perceived profit indicator of maize production. It is assumed that farmers make profitability-based decisions based on passed observations.

Private fertilizer expenditure = MAX(share maize income to fertilizer, 0)*Aggregated Farm Income Maize Real

Units: Rlc/Year

This variable represents annual fertilizer expenditures spent by farmers (in real local currency: Zambian Kwacha94). In line with microeconomic theory, this variable assumes that the higher the income, the higher also the expenditure for a certain good (here fertilizer). Source: Varian H.R. 2007. Grundzüge der Mikroökonomik. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

Producer price maize real = IF THEN ELSE(Time<2011, MAX(indicated producer price maize,FLOOR price namboard and food reserve agency real), indicated producer price maize)

Units: Rlc/Kg

This variable represents the producer price of maize (in real local currency per kilogram). In the past, the variable takes the maximum value of the indicated producer price on the market and the floor price determined by the pubic Food Reserve Agency (FRA). For simulating the future, only the indicated producer price is applied because the FRA floor price follows is rather undeterminable (determined in a political process). Producer price is a variable part of many feedback loops. Still it was not used as a main variable for calibration since long-term data is scarce and from 1988 to 1995 even missing. Thus, the focus was on the main trend, however, not on the variation.

PUBLIC expenditure for fertilizer subsidies: INTERPOLATE

Units: Rlc/Year

This variable represents the past trajectories of annual PUBLIC expenditure for fertilizer subsidies in real local currency (Zambian Kwacha94). It is an exogenous model input taken from several data source. Data sources: Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA; Howard J.A., Chitalu G.M., Kalonge S.M. 1993. The impact of investments in maize research and dissemination in Zambia part one: main report, Michigan State University: Michigan, USA; Zulu B., Nijhoff J.J., Jayne T.S., Negassa A. 2000. Is the glass half-empty or half full? an analysis of agricultural production trends in Zambia, FSRP: Lusaka, Zambia; Chiwele D., Fowler M., Humphrey E., Hurrell A., Willis J. 2010. Agriculture case study. Evaluation of Budget Support in Zambia, 2010; GRZ. Various years. Estimates of Revenue and Expenditure (including Capital and Constitutional and Statutory Expenditure). GRZ, Lusaka, Zambia.

Relative perceived food maize supply = Perceived Food Supply Maize/INITIAL PERCEIVED FOOD SUPPLY MAIZE
Units: Dmnl
This variable represents the relative state of farmers' perception of maize supply compared to the initial value.

Relative perceived gross profit per hectare maize = Perceived Gross Profit Per Hectare Maize/INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE
Units: Dmnl
This variable represents the perceived per area gross profit indicator of maize production relative to its initial value.

RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION = 0.5
Units: Dmnl
This variable represents the weight farmers allocate to the profitability of maize relative to the availability within their decision process of selling maize. Since both factors (food and cash) are essential, they are assumed to be equally important.

Sales maize = maize production*share of maize production sold
Units: Ton/Year
This variable represents the annual amount of maize being sold at a market. In western countries this variable would typically be equal to the production. In the case

of Zambia, maize is partly sold and partly self-consumed. Thus, this variable is only a share of the total production, and the producers consume the rest. Source: Chapoto A., Haggblade S., Hichaambwa M., Kabwe S., Longabaugh S., Sitko N., Tschirley D. 2012. Agricultural Transformation in Zambia: Alternative Institutional Models for Accelerating Agricultural Productivity Growth and Commercialization, IAPRI: Lusaka, Zambia.

Share maize income to fertilizer = IF THEN ELSE(Time<2010, SHARE of farm income maize to fertilizer, AVERAGE SHARE OF FARM INCOME MAIZE TO FERTILIZER 1984 TO 2009)
Units: Dmnl
This variable represents the share of income (derived from maize sales) that farmers spend on fertilizer purchases. It represents a budget allocation decision of farmers. Potentially, this share could be derived endogenously. However, because fertilizers often are not available for purchase at the right place and time, and little is known about the decision rules of Zambian farmers in regard to fertilizer allocation, the representation with a fraction was deemed most adequate.

SHARE of farm income maize to fertilizer: INTERPOLATE
Units: Dmnl
This is an exogenous model input representing the historic share of maize income that farmers spend on fertilizer purchases.

SHARE of fertilizer expenditure on nitrogen: INTERPOLATE
Units: Dmnl
This variable determines the share of fertilizer expenditures that are spent on nitrogen. (The rest is spent for other fertilization elements, e.g. phosphorus and potassium). The variable is an exogenous input based on estimated data. The last value is used for future scenario building. Data sources: Wood A.P., Kean S.A., Milimo J.T., Warren D.M. 1990. The Dynamics of Agricultural Policy and Reform in Zambia. Iowa State University Press: Ames, Iowa, USA; Kumar S.K. 1988. Design, Income Distribution, and Consumption Effects of Maize Pricing Policies in Zambia.

In Food Subsidies in Developing Countries, Published for International Food Policy Research Institute. Johns Hopkins University Press: Baltimore, USA, pp 289 – 300; Mason N.M., Myers R.J. 2013. The effects of the Food Reserve Agency on maize market prices in Zambia. Agricultural Economics, 44, (2), 203-216; MAOC. Various years. Provincial Prices from 1994 to 2012. Ministry of Agriculture and Cooperatives, Lusaka, Zambia.

Share of maize production sold = MIN(indicated share of production sold from maize gross profit*RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION+indicated share of production sold from maize availability*(1-RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION), 1)
Units: Dmnl
This variable represents the share of the total production that is sold on a market. It is determined by two factors: the farmers' need for food and the farmers' need for cash. If there is enough maize, the share increases because farmers are assumed to have extra maize to sell and in a situation with maize scarcity, the share decreases because farmers are assumed to retain maize for self-consumption. On the other hand, if profits of maize production are high, farms are more likely to sell maize for earning cash.

START TIME CONTINOUS REDUCTION = 2015
Units: Year
This constant is only used in experiment 8 (see Article 1) and determines when the linear decrease in fertilizer subsidy program expenditures starts.

SWITCH FERTILIZER SUBSIDY DROP = 0
Units: Dmnl
This constant activates or deactivates the drop in fertilizer subsidy program expenditures. If the constant is set to value 1, the drop happens (in experiments 3, 5 and 7), if the constant is set to the value 0 the decrease does not happen (in experiments 1,2,4,6 and 8).

TIME TO ADJUST FARM INCOME MAIZE = 1
Units: Year
This constant represents the time between two growing seasons.

TIME TO PERCEIVE FOOD MAIZE SUPPLY = 0.3
Units: Year
This constant represents the time frame over which farmers perceive the maize supply situation.

TIME TO PERCEIVE PER HECTARE MAIZE GROSS PROFIT = 3
Units: Year
This constant represents the time horizon over which adjustment in gross profitability perception is made.

Total fertilizer expenditures real = private fertilizer expenditure+expenditure fertilizer subsidy program
Units: Rlc/Year
This variable represents the total annual fertilizer expenditure including private and public sources (in real local currency: Zambian Kwacha 94).

Total nitrogen fertilizer expenditure real = total fertilizer expenditures real*SHARE of fertilizer expenditure on nitrogen
Units: Rlc/Year
This variable represents the annual amount of total fertilizer expenditures going to nitrogen (in real local currency: Kwacha 94).

A.3.6 Food Availability Sector

AVERAGE DIETARY ENERGY REQUIREMENT = 2200
Units: Kcal/(Person*Day)
This variable represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organization of the United Nations (FAO) that calculate this parameter dependent on several population

characteristics (e.g. age structure, level of physical activity, etc.). While the FAO value slightly changes over time, for simplicity, I assume a constant value of 2200 being realistic for the case of Zambia.

CONSUMPTION animal products: INTERPOLATE
Units: Kcal/(Person*Day)
This variable represents the number of total kilocalories from animal products that are on average consumed per person per day. Because of the little amount of animal products in the Zambian diet, this variable is exogenously taken from data (FAO, 2014) and added to the model for completeness. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Consumption maize products = per capita food maize consumption kcal per year/DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the number of kilocalories from maize products that are consumed per person per day. It is a key indicator for measuring the food production system's performance. Reference data is taken from FAO (2014). Simulation results compared to historical data seem to fit badly at the first glance. However, the FAO data series for maize consumptions has major flaws. When data is put in a dynamic context and inventory levels are calculated, the data suggests that at a point in time the maize inventory level reaches five times the quantity of a normal annual maize harvest. Thus, while the maize inventories seem to overflow, people simultaneously suffer from hunger. This is unrealistic. Therefore the divergence of simulation results compared to data is acceptable and other, more reliable variables such as yield, production and land allocation are better suited for calibration. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Consumption vegetal products = per capita plant consumption kcal per year/DAYS PER YEAR

Units: Kcal/(Person*Day)
This variable represents the number of kilocalories from vegetal products that are on average consumed per person per day. (Excluding calories from animal sources). Reference data is taken from FAO (2014). Simulation results compared to historical data seem to fit badly at the first glance. However, the FAO data series for vegetal products consumptions has major flaws, at least for the single most important food item “maize”. When data is put in a dynamic context and inventory levels are calculated, the data suggests that at a point in time the maize inventory level reaches five times the quantity of a normal annual maize harvest. Thus, while the inventories seem to overflow, people simultaneously suffer from hunger. This is unrealistic. Therefore the divergence of simulation results compared to data is acceptable and other, more reliable variables such as yield, production and land allocation are better suited for calibration. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

DAYS PER YEAR = 365
Units: Day/Year
This constant represents the number of days per year (365).

Domestic maize consumption = MIN(domestic maize demand, potential domestic maize supply)
Units: Ton/Year
This variable represents the domestic maize consumption that is withdrawn from the inventories. If demand is higher than potential supply, this variable equals potential supply. And if potential supply is higher than demand, this variable equals demand.

ENERGY share of maize on total diet: INTERPOLATE
Units: Dmnl
This variable represents the past share of kilocalories coming from maize compared to the total diet. The past trajectory was calculated from FAO, and last value is applied as future scenario. Source: calculated from FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Food consumption = consumption vegetal products+CONSUMPTION animal products
Units: Kcal/(Person*Day)
This variable represents the number of kilocalories that are consumed per person per day. It is a key indicator for measuring the food production system's performance. Reference data is taken from FAO (2014). Simulation results compared to historical data seem to fit badly at the first glance. However, the FAO data series for food consumptions has major flaws, at least for the single most important food item "maize". When data is put in a dynamic context and inventory levels are calculated, the data suggests that at a point in time the maize inventory level reaches five times the quantity of a normal annual maize harvest. Thus, while the inventories seem to overflow, people simultaneously suffer from hunger. This is unrealistic. Therefore the divergence of simulation results compared to data is acceptable and other, more reliable variables such as yield, production and land allocation are better suited for calibration. Data source: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Kcal net import plant = IF THEN ELSE(Time<2012, TOTAL kcal net import plant, TOTAL KCAL NET IMPORT PLANT FROM 2011 ON)
Units: Kcal/Year
This variable is used to combine the past development of plant import (Total Kcal Net Import Plant) with its future scenario (TOTAL KCAL NET IMPORT PLANT from 2011 on).

Kcal non maize non food use = PER capita kcal non maize non food use*TOTAL population
Units: Kcal/Year
This variable represents the annual non-food consumption of non-maize plant products in kilocalories. Since demand for non-food, non-maize vegetal products is not modeled endogenously, this variable depends on data. For future scenario building the per capita use is multiplied with the population scenario.

KCAL PER KG MAIZE = 3071
Units: Kcal/Kg
This variable represents the number of kilocalories per kilogram maize. It is estimated from FAO data. (FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.)

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

Maize availability = potential domestic maize supply*KG PER TON*KCAL PER KG MAIZE/TOTAL population/DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the number of kilocalories from maize products that are on average available per person per day. Maize availability is a main target variable of fertilizer subsidy programs and a major food system outcome in Zambia. Thus, it is a suitable variable for evaluating the fertilizer subsidy policy's success.

Maize energy requirement = AVERAGE DIETARY ENERGY REQUIREMENT*ENERGY share of maize on total diet
Units: Kcal/(Person*Day)
This variable represents a person's caloric requirement coming from maize products. Included in this variable is the physical need for maize and the preference for maize compared to other food products. Not included is the adjustment of the demand to prices.

Maize for non food use = maize for seed use+(SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER+SHARE OF MAIZE PRODUCTION WASTE)*potential domestic maize supply
Units: Ton/Year
This variable represents the annual maize demand for non-food purposes including seed, animal odder and food waste.

Net import maize = IF THEN ELSE(Time<2012, IMPORT maize-EXPORT maize, IMPORT MAIZE SCENARIO AFTER 2011-EXPORT MAIZE SCENARIO AFTER 2011)
Units: Ton/Year
This variable calculates the net import of maize to Zambia (net import = import - export).

Net import non maize plant products = kcal net import plant-net import maize*KG PER TON*KCAL PER KG MAIZE
Units: Kcal/Year
This variable represents the caloric amount of plant products that are net imported, without maize.

Non maize production = area harvested non maize*yield non maize
Units: Kcal/Year
This variable represents the production of plant products other than maize.

Per capita food maize consumption kcal per year = total food maize consumption in kcal/TOTAL population
Units: Kcal/(Year*Person)
This variable represents the total number of kilocalories from maize products that are consumed per person per year. It is an intermediate variable used to calculate "consumption maize products".

PER capita kcal non maize non food use: INTERPOLATE
Units: Kcal/(Person*Year)
This variable represents the non-food consumption of plant products other than maize in kilocalories on a per capita, annual basis. Since demand for non-food, non-maize vegetal products is not modeled endogenously, this variable is taken from data. The last value is used for scenario building. Data source: calculate from FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Per capita plant consumption kcal per year = total food plant consumption in kcal/TOTAL population
Units: Kcal/(Year*Person)
This variable represents the number of kilocalories from plant products that are consumed per person per year. (Excluding calories from animal sources). It is an intermediate variable used to calculate "consumption vegetal products".

Potential domestic maize supply = maize production+net import maize+Maize Inventory/INVENTORY HANDLING TIME
Units: Ton/Year
This variable represents the maize quantity that can be maximally supplied to the market. It includes the current production as well as production from previous years that are stored in maize inventories. Conceptually it is taken from Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Total food maize consumption in kcal = total food maize consumption in tons*KG PER TON*KCAL PER KG MAIZE
Units: Kcal/Year
This variable represents the number of kilocalories from maize products that are annually consumed as food by Zambians. It is an intermediate variable used to calculate "consumption maize products".

Total food maize consumption in tons = domestic maize consumption-maize for non food use
Units: Ton/Year
This variable represents the total number of tons from maize products that are annually consumed as food by Zambians. It is an intermediate variable used to calculate "consumption maize products".

Total food plant consumption in kcal = non maize production+net import non maize plant products-kcal non maize non food use+total food maize consumption in kcal
Units: Kcal/Year

This variable represents the number of kilocalories from vegetal products that are annually consumed by Zambians. (Excluding calories from animal sources). It is an intermediate variable used to calculate "consumption vegetal products".

TOTAL kcal net import plant: INTERPOLATE
Units: Kcal/Year
This variable represents the past development of the number of plant calories imported to Zambia. Because trade is represented exogenously (due to its politically driven unpredictability), this variable is taken from FAO data. Data source: calculated from FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

TOTAL KCAL NET IMPORT PLANT FROM 2011 ON = 0
Units: Kcal/Year
This constant represents the future scenario for the plant calories that are imported to Zambia. The value is set to zero. The reason is an assumed goal of food self-sufficiency. It is clear that food trade is an option for Zambia and most likely will happen in the future. However, from an endogenous point of view, it is interesting to study the dynamics internal of the food production system. Therefore, and because food trade is politically motivated and difficult to foresee, the value of zero is applied. Scenario analysis revealed that the main study results are robust under different development patterns.

TOTAL population: INTERPOLATE
Units: Person
This variable represents the total population. Total population is an exogenous input to the model and both - data for the past and the scenario for the future - are taken from FAO (2014). Malthusian theory states that the population level is dependent on food availability. By using population as an exogenous model input I do not want to challenge this theory. Such a link from food availability to population could potentially be implemented in the model (and was tested). However, population also depends on other determinants that are not represented in the model (physical and

socio-economic phenomena). By implementing just the single link from food availability to population I would pretend a population study based on weak theory and the study would loose its focus on food production system. Thus, I exclude this link and analyze how the system reacts to the exogenous input. Data source: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

A.4 Data

This section contains the data that was used for the model of Article 1. Some data series served as model inputs, some define scenarios for the future and some series were used to calibrate the model. An overview of the usage and the source of the data is presented in Article 1.

Data used by the model of Article 1.

Time	ARABLE LAND	ARABLE LAND AND PERMANENT CROPS	AREA HARVESTED MAIZE	AREA HARVESTED NON MAIZE	AVERAGE DIETARY ENERGY REQUIREMENT	CONSUMER PRICE MAIZE
1984	834692	2332000	506500	328192		177.8
1985	926411	2425000	581846	344565		126.0
1986	988797	2485000	588490	400307		96.5
1987	1088030	2586000	609529	478503		
1988	1213890	2709000	723087	490803		
1989	1552410	3047000	1020570	531838		
1990	1316030	2911000	763277	552749		
1991	1178500	2776000	639390	539112		
1992	1205280	2800000	661305	543972	2096	
1993	1215700	2802000	633326	582378	2085	
1994	1279600	2873000	679355	600242	2086	196.1
1995	1075440	2673000	520165	555273	2087	231.0
1996	1303490	2900000	675565	627922	2088	254.2
1997	1238420	2836000	649039	589380	2087	194.7
1998	1128340	2725000	510372	617969	2085	260.6
1999	1333250	2925000	597454	735797	2084	217.7
2000	1256890	2848000	586907	669987	2082	160.1
2001	1162920	2755000	582000	580921	2080	157.7
2002	1027740	2616000	430000	597736	2079	222.6
2003	1323280	2909000	671000	652277	2080	183.5
2004	1323950	2897000	631000	692953	2083	127.6
2005	1206860	2762000	465832	741031	2088	130.9
2006	1524410	3048000	750000	774410	2093	117.7
2007	1304160	2984000	585291	718872	2099	98.9
2008	1321950	3087000	539877	782074	2103	145.2
2009	1901020	3385000	911942	989080	2106	153.5
2010	2129270	3735000	1080560	1048710	2107	107.9
2011	2053460	3435000	1036080	1017380	2109	78.8

Data used by the model of Article 1.

Time	CONSUMPTION ANIMAL PRODUCTS	CONSUMPTION MAIZE PRODUCTS	CONSUMPTION VEGETAL PRODUCTS	COUNTRY AREA	ENERGY SHARE OF MAIZE ON TOTAL DIET	EXPORT MAIZE
1984	98	1278	2022	75261000	0.6028	0
1985	105	1285	1919	75261000	0.6346	1000
1986	99	1293	1934	75261000	0.6360	35000
1987	99	1303	1938	75261000	0.6397	0
1988	98	1347	1971	75261000	0.6510	0
1989	101	1275	1970	75261000	0.6156	1000
1990	118	1217	1940	75261000	0.5911	17000
1991	119	1194	1913	75261000	0.5876	1000
1992	123	1184	1879	75261000	0.5914	0
1993	116	1133	1872	75261000	0.5699	10000
1994	118	1186	1912	75261000	0.5839	3000
1995	106	1248	1954	75261000	0.6058	3000
1996	103	1221	1939	75261000	0.5979	2000
1997	111	1134	1867	75261000	0.5733	9000
1998	109	1125	1816	75261000	0.5844	0
1999	112	1093	1853	75261000	0.5562	9000
2000	106	1015	1773	75261000	0.5402	17000
2001	105	999	1762	75261000	0.5348	20000
2002	106	995	1748	75261000	0.5367	5000
2003	105	994	1800	75261000	0.5218	37000
2004	103	956	1769	75261000	0.5107	107000
2005	105	941	1775	75261000	0.5005	59000
2006	100	927	1746	75261000	0.5022	29000
2007	108	950	1678	75261000	0.5322	229000
2008	107	906	1706	75261000	0.4997	210000
2009	111	917	1776	75261000	0.4860	32000
2010	114	940	1797	75261000	0.4921	69000
2011	109	972	1828	75261000	0.5018	521000

Data used by the model of Article 1.

Time	FARM INCOME MAIZE REAL	FEED MAIZE	FLOOR PRICE NAMBOARD AND FOOD RESERVE AGENCY REAL	FOOD CONSUMPTION	"GDP DEFLATOR (BASE 1994)"	GROSS PROFIT PER HECTARE MAIZE
1984	66956898304	30000	117.26	2120	0.23215	157630
1985	65113899008	30000	96.04	2025	0.32765	185750
1986	97772896256	35000	102.49	2033	0.59628	230032
1987	58582200320	30000	89.71	2037	0.96605	137002
1988		30000	0	2069	1.29924	
1989		30000	0	2071	2.35004	
1990		30000	0	2059	4.85022	
1991		30000	0	2032	9.34417	
1992		30000	0	2002	24.81190	
1993		30000	0	1988	60.45630	
1994		30000	0	2031	100	
1995		25000	0	2060	138.04500	
1996	48897998848	25000	0	2042	169.6750	124772
1997	31224199168	25000	73.73	1978	213.7390	123741
1998	22331199488	30000	0	1925	255.3980	131864
1999	21026299904	33000	0	1965	309.9310	115160
2000	13361300480	25000	0	1879	405.24799	116703
2001	33740599296	25000	0	1868	503.61600	133966
2002	29164199936	25000	132.65	1854	603.11102	99006.10156
2003	43143798784	25000	83.08	1905	722.23401	72252.10156
2004	29679300608	25000	83.08	1872	866.65399	40671.19922
2005	26428399616	20000	71.00	1880	1014.1500	83881.20313
2006		30000	66.16	1846	1148.7300	65052.19922
2007	33906999296	25000	58.63	1785	1296.2700	75521.29688
2008	38233300992	25000	75.81	1813	1451.07996	91958.10156
2009	55403298816	30000	80.63	1887	1612.30005	107341
2010		55000	72.19	1910	1800.7300	
2011		65000		1937	2025.4600	

Data used by the model of Article 1.

Time	IMPORT MAIZE	INLAND WATER	KCAL NON MAIZE NON FOOD USE	MAIZE FOR NON FOOD USE	MAIZE FOR SEED USE	MAIZE PRODUCTION
1984	144000	922000	93867401216	80455	17455	871740
1985	130000	922000	1.00167E+11	85655	17655	1122350
1986	65000	922000	1.40067E+11	92286	18286	1230590
1987	87000	922000	1.50387E+11	88693	21693	1063450
1988	140000	922000	1.44909E+11	122617	30617	1943220
1989	90000	922000	1.63609E+11	110898	22898	1844980
1990	100000	922000	1.68461E+11	87182	19182	1092670
1991	44000	922000	1.68805E+11	87839	19839	1095910
1992	680000	922000	1.68865E+11	87000	19000	483492
1993	316000	922000	2.15845E+11	107381	20381	1597770
1994	14000	922000	2.27276E+11	85605	15605	1020750
1995	113000	922000	2.46607E+11	88267	20267	737835
1996	54000	922000	2.32003E+11	87471	19471	1409490
1997	53000	922000	2.50576E+11	81311	15311	960188
1998	444000	922000	2.46564E+11	88924	17924	638134
1999	22000	922000	2.73182E+11	92607	17607	822056
2000	8000	922000	2.57949E+11	82460	17460	1040000
2001	24000	922000	2.82879E+11	77900	12900	802000
2002	168000	922000	2.48571E+11	85130	20130	606172
2003	132000	922000	2.42358E+11	86930	18930	1157860
2004	10000	922000	2.92953E+11	83975	13975	1214000
2005	39000	922000	3.36051E+11	86500	22500	866187
2006	124000	922000	4.38324E+11	93559	17559	1424400
2007	3000	922000	4.37196E+11	93196	16196	1366160
2008	3000	922000	4.47401E+11	102358	27358	1211570
2009	43000	922000	4.80397E+11	120417	32417	1887010
2010	7000	922000	5.26845E+11	170082	31082	2795480
2011	4000	922000	6.68103E+11	187082	31082	2496430

Data used by the model of Article 1.

Time	MAIZE YIELD	NITROGEN FERTILIZER APPLICATION	NITROGEN FERTILIZER PRICE REAL DATA	NON MAIZE PRODUCTION	ORGANIC MATTER FROM ANIMALS	ORGANIC NITROGEN FROM ANIMALS
1984	1.7211	37776	578.080	1.66463E+12	63632.8	5693.4
1985	1.9289	53351	409.587	1.68898E+12	69779.4	6203.6
1986	2.0911	53814	513.182	1.68301E+12	72033.0	6430.3
1987	1.7447	61817	316.754	1.84629E+12	74256.5	6653.7
1988	2.6874	56080	268.695	2.0775E+12	76265.5	6873.4
1989	1.8078	51800	834.561	2.2907E+12	85894.2	8230.6
1990	1.4316	37900	463.526	2.27808E+12	89632.5	8471.4
1991	1.7140	40091	437.931	2.36395E+12	93164.0	8734.9
1992	0.7311	57300	631.599	2.09972E+12	95048.8	8832.8
1993	2.5228	57900	774.715	2.66276E+12	96698.0	9043.9
1994	1.5025	38000	608.945	2.63106E+12	99274.5	9283.0
1995	1.4185	34000	926.325	2.38771E+12	91880.2	8723.8
1996	2.0864	27500	898.843	2.90453E+12	92693.5	8958.4
1997	1.4794	32600	857.210	2.79417E+12	94937.7	9100.6
1998	1.2503	13200	805.537	2.81015E+12	98693.5	9406.3
1999	1.3759	10621	734.767	3.5495E+12	102957.0	9733.9
2000	1.7720	8000	751.580	2.98134E+12	102957.0	9627.7
2001	1.3780	13000	666.917	2.98179E+12	107300.0	10055.9
2002	1.4097	36815.5	605.701	3.22947E+12	103522.0	9437.6
2003	1.7256	42816	606.689	3.49815E+12	102313.0	9298.4
2004	1.9239	60177	743.317	3.52962E+12	103420.0	9514.6
2005	1.8594	51637	567.788	3.92913E+12	108343.0	9963.8
2006	1.8992	49225	486.809	3.95483E+12	117325.0	11302.8
2007	2.3342	55754	471.447	3.84537E+12	127949.0	13104.3
2008	2.2442	53215	666.402	3.85735E+12	143887.0	15484.9
2009	2.0692	64145	749.735	5.28195E+12	153535.0	16200.2
2010	2.5871	77617	506.287	5.63947E+12	157191.0	16495.6
2011	2.4095	116486	495.290	6.26353E+12	158054.0	16592.2
2030					203365.0	20246.3
2050					317249.0	32632.6

Data used by the model of Article 1.

Time	OTHER LAND	PER CAPITA KCAL NON MAIZE NON FOOD USE	POTENTIAL DOMESTIC MAIZE SUPPLY	PRECIPITATION DATA	PROCESSING MAIZE	PRODUCER PRICE MAIZE REAL
1984		14143.0	1115000	753.66	26000	117.262
1985		14648.6	1152000	934.85	22000	96.038
1986		19893.1	1201000	1014.79	27000	102.487
1987		20760.3	1240000	795.40	30000	89.712
1988		19461.3	1343000	888.23	28000	
1989		21395.2	1295000	1065.25	25000	
1990	728000	21473.7	1246000	876.46	24000	
1991	879600	21000.9	1259000	756.58	30000	
1992	807200	20520.7	1274000	675.25	28000	
1993	836800	25625.7	1274000	985.97	33000	
1994	732400	26350.8	1332000	693.74	30000	
1995	914000	27893.6	1433000	623.98	33000	
1996	673600	25570.7	1437000	823.68	32000	73.187
1997	734200	26885.9	1369000	930.52	31000	100.186
1998	846800	25745.5	1402000	800.64	32000	127.508
1999	633400	27765.2	1400000	906.49	29000	84.105
2000	707000	25537.0	1330000	836.31	28000	71.153
2001	816600	27299.7	1336000	1018.65	27000	115.391
2002	922200	23394.9	1369000	727.82	27000	127.812
2003	795800	22244.9	1403000	905.93	28000	72.964
2004	974400	26215.0	1381000	930.76	28000	61.680
2005	1276000	29298.3	1397000	739.87	28000	75.567
2006	1156600	37202.9	1420000	932.49	28000	47.713
2007	1387200	36102.1	1491000	969.70	30000	51.183
2008	1450800	35915.6	1474000	1086.76	29000	71.559
2009	1319400	37457.8	1548000	1018.49	30000	67.539
2010	1136000	39861.2	1683000	1053.67	34000	
2011	1602600	49002.7	1803000	898.74	39000	

Data used by the model of Article 1.

Time	PUBLIC EXPENDITURE FOR FERTILIZER SUBSIDIES	SALES MAIZE	SHARE OF FARM INCOME MAIZE TO FERTILIZER	SHARE OF FERTILIZER EXPENDITURE ON NITROGEN	SHARE OF MAIZE ON TOTAL AREA HARVESTED	SHARE OF MAIZE PRODUCTI ON SOLD
1984	8582900224	571000	0.33428	0.70522	0.60681	0.65501
1985	31344699392	678000	0.00000	0.70370	0.62806	0.60409
1986	47377100800	954000	0.00000	0.72435	0.59516	0.77524
1987	17048800256	653000	0.20310	0.67645	0.56021	0.61404
1988	12676599808	1007000		0.65796	0.59568	0.51821
1989	12170000384	1219620		0.70925	0.65741	0.66105
1990	15669399552	601165		0.58199	0.57999	0.55018
1991	20761899008	602884		0.51708	0.54255	0.55012
1992	25854500864	258965		0.71009	0.54868	0.53562
1993	29365899264	929837		0.76215	0.52095	0.58196
1994	6656280064	476288		0.70276	0.53091	0.46661
1995	12920999936	344676		0.77753	0.48368	0.46714
1996	19577300992	668123	0.38581	0.64299	0.51828	0.47402
1997	29365899264	311662	0.50873	0.61756	0.52409	0.32458
1998	11746400256	175136	0.62986	0.41195	0.45232	0.27445
1999	19577300992	250001	0.01589	0.39193	0.44812	0.30412
2000	12421499904	187783	0.41203	0.33540	0.46695	0.18056
2001	7942559744	292401	0.43198	0.38503	0.50046	0.36459
2002	2949710080	228181	1.19678	0.58910	0.41840	0.37643
2003	6922959872	591300	0.83448	0.60514	0.50707	0.51068
2004	11313699840	481183	1.65821	0.73900	0.47660	0.39636
2005	13803499520	349734	0.99814	0.72964	0.38599	0.40376
2006	16021600256			0.68088	0.49199	
2007	15760499712	662470	0.75864	0.63362	0.44879	0.48491
2008	31825999872	534294	0.96915	0.51485	0.40839	0.44099
2009	35050799104	820318	0.53348	0.74437	0.47971	0.43472
2010	23879100416			0.80304	0.50748	
2011	23945199616			0.71415	0.50455	

Data used by the model of Article 1.

Time	SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER	SHARE OF MAIZE PRODUCTION WASTE	SHORT TERM MEADOWS	SUBSIDY PER KG MAIZE REAL	TOTAL FERTILIZER EXPENDITURES REAL	TOTAL FOOD MAIZE CONSUMPTION IN TONS
1984	0.026906	0.029596	1500000	10.33820	30965499904	1008000
1985	0.026042	0.032986	1500000	34.72570	31052800000	1044000
1986	0.029142	0.032473	1500000	57.41150	38125600768	1082000
1987	0.024193	0.029839	1500000	73.55380	28946499584	1121000
1988	0.022338	0.046165	1500000	95.41110	22901700608	1192000
1989	0.023166	0.044788	1500000	45.35700	60951699456	1159000
1990	0.024077	0.030498	1500000	89.30710	30185598976	1134000
1991	0.023828	0.030183	1500000	0.00000	33954500608	1141000
1992	0.023548	0.029827	1500000	0.00000	50965901312	1158000
1993	0.023548	0.044741	1500000	0.00000	58854600704	1134000
1994	0.022522	0.030030	1500000	0.00000	32927000576	1216000
1995	0.017446	0.030007	1500000	0.00000	40506499072	1311000
1996	0.017397	0.029924	1500000	0.00000	38442500096	1317000
1997	0.018261	0.029949	1500000	0.00000	45250699264	1256000
1998	0.021398	0.029244	1500000	0.00000	25811900416	1281000
1999	0.023571	0.030000	1500000	0.00000	19911499776	1278000
2000	0.018797	0.030075	1500000	0.00000	17926799360	1219000
2001	0.018713	0.029940	1500000	0.00000	22517700608	1231000
2002	0.018261	0.029218	1500000	0.00000	37852901376	1256000
2003	0.017819	0.030649	1500000	12.22880	42925600768	1287000
2004	0.018103	0.032585	1500000	11.31770	60528201728	1270000
2005	0.014316	0.031496	1500000	16.67130	40182898688	1283000
2006	0.021127	0.032394	1500000		35194601472	1298000
2007	0.016767	0.034876	1500000	23.87230	41483599872	1367000
2008	0.016961	0.033921	1500000	10.31860	68879597568	1342000
2009	0.019380	0.037468	1500000	14.99380	64607199232	1398000
2010	0.032680	0.049911	1500000		48934801408	1477000
2011	0.036051	0.050471	1500000		80787701760	1575000

Data used by the model of Article 1.

Time	TOTAL KCAL NET IMPORT PLANT	TOTAL NITROGEN FERTILIZER EXPENDITURE REAL	VALUE ADDED REAL	WASTE MAIZE	YIELD NON MAIZE DATA
1984	9.05549E+11	21837600768	70.884	33000	5072120
1985	6.14847E+11	21851899904	64.670	38000	4901780
1986	3.76059E+11	27616399360	51.430	39000	4204290
1987	3.74394E+11	19580798976		37000	3858470
1988	5.7043E+11	15068399616		62000	4232860
1989	4.79425E+11	43230298112		58000	4307150
1990	6.12533E+11	17567600640		38000	4121370
1991	1.59119E+11	17557100544		38000	4384900
1992	2.19428E+12	36190601216		38000	3859980
1993	1.06866E+12	44856000512		57000	4572220
1994	2.68366E+11	23139899392		40000	4383340
1995	5.56023E+11	31495000064		43000	4300060
1996	3.05534E+11	24718200832	181.058	43000	4625620
1997	3.23054E+11	27945000960	94.469	41000	4740870
1998	1.45805E+12	10633100288	133.109	41000	4547400
1999	1.0748E+11	7803959808	133.579	42000	4824020
2000	1.4522E+11	6012639744	88.964	40000	4449840
2001	3.72986E+11	8669920256	42.292	40000	5132870
2002	7.19688E+11	22299199488	94.741	40000	5402830
2003	5.7886E+11	25976000512	122.805	43000	5362980
2004	1.66033E+11	44730601472	77.216	45000	5093590
2005	4.52595E+11	29318899712	71.957	44000	5302250
2006	8.15929E+11	23963199488		46000	5106890
2007	-7.85044E+11	26285099008	71.620	52000	5349180
2008	-2.50044E+11	35462598656	83.993	50000	4932210
2009	270180992	48091701248	100.998	58000	5340260
2010	-7.50139E+11	39296499712		84000	5377530
2011	-1.9721E+12	57694400512		91000	6156520

Data used by the model of Article 1.

Time	RURAL POPULATION	TOTAL ECONOMICALLY ACTIVE POPULATION IN AGRICULTURE	TOTAL POPULATION	Time	RURAL POPULATION	TOTAL ECONOMICALLY ACTIVE POPULATION IN AGRICULTURE	TOTAL POPULATION
1984	4002000	1728000	6637000	2018	9869000	4096000	17111000
1985	4127000	1805000	6838000	2019	10109000	4214000	17673000
1986	4252000	1886000	7041000	2020	10352000	4333000	18252000
1987	4379000	1968000	7244000	2021	10597000		18847000
1988	4505000	2051000	7446000	2022	10844000		19457000
1989	4630000	2132000	7647000	2023	11093000		20084000
1990	4753000	2210000	7845000	2024	11343000		20727000
1991	4904000	2273000	8038000	2025	11595000		21388000
1992	5060000	2311000	8229000	2026	11849000		22066000
1993	5219000	2353000	8423000	2027	12103000		22761000
1994	5385000	2387000	8625000	2028	12358000		23475000
1995	5561000	2427000	8841000	2029	12614000		24206000
1996	5749000	2474000	9073000	2030	12870000		24957000
1997	5948000	2521000	9320000	2031	13127000		25726000
1998	6157000	2567000	9577000	2032	13383000		26514000
1999	6370000	2613000	9839000	2033	13640000		27322000
2000	6586000	2658000	10101000	2034	13895000		28150000
2001	6740000	2702000	10362000	2035	14151000		28998000
2002	6867000	2744000	10625000	2036	14407000		29867000
2003	6996000	2787000	10895000	2037	14663000		30757000
2004	7130000	2835000	11175000	2038	14919000		31668000
2005	7271000	2885000	11470000	2039	15174000		32599000
2006	7419000	2941000	11782000	2040	15429000		33552000
2007	7574000	3010000	12110000	2041	15684000		34525000
2008	7739000	3082000	12457000	2042	15937000		35518000
2009	7913000	3161000	12825000	2043	16188000		36533000
2010	8099000	3246000	13217000	2044	16438000		37568000
2011	8296000	3337000	13634000	2045	16686000		38624000
2012	8503000	3434000	14075000	2046	16932000		39700000
2013	8719000	3536000	14539000	2047	17175000		40797000
2014	8941000	3642000	15021000	2048	17415000		41914000
2015	9168000	3752000	15520000	2049	17651000		43051000
2016	9398000	3864000	16034000	2050	17885000		44206000
2017	9632000	3979000	16564000				

Appendix B

Model Documentation Article 2

B.1 Purpose and Scope of the Model

Article 2 is based on a system dynamics simulation model and seeks to explain why food availability is enduringly low in sub-Saharan Africa (SSA). The model is of illustrative nature, it captures the key processes of the SSA food production system on an aggregated, national level, and it runs over decades (0-200 years). Plant production is endogenously captured and animal based production is represented by exogenous variables. The model structure was developed by condensing the model of Article 1 and was specified in Vensim software. The model was set in dynamic equilibrium for analyzes purposes.

B.2 Summary Statistics of the Model

According to the Vensim software, the unit’s within the model are consistent and the syntax is complete. The model was not sensitive to changes in values of the time step and integration methods.

The following summary statistics are based on the SDM-Doc tool that is available on the Systems Dynamics Society homepage (http://tools.systemdynamics.org/sdm-doc/; accessed: 25 April 2017).

Summary statistics of the model that underlies Article 2

Model information	**Result**
Total number of variables	75
Total number of stocks	6 (8.0%)
Total number of feedback loops	12
Whereof reinforcing	5
Whereof balancing	7
Total number of causal links	97
Total number of macros	0
Variables with source information	0
Dimensionless unit variables	17 (22.7%)
Variables without predefined min or max value	71 (94.7%)
Function sensitivity parameters	0
Data lookup tables	0
Time unit	Year
Initial time	0
Final time	200
Reported time interval	1
Time step	0.0625
Model is fully formulated	Yes
Warnings	**Result**
Number of undocumented variables	0
Equations with embedded data	2 (2.7%)
Variables not in any view	0
Nonmonotonic lookup functions	0
Cascading lookup functions	0
Non-zero end sloped lookup functions	0
Equations with if then else functions	0
Equations with min or max functions	4 (5.3%)
Equations with step pulse or related functions	1 (1.3%)
Potential Omissions	**Result**
Unused variables	0
Supplementary variables	2 (2.7%)
Supplementary variables being used	0
Complex variables (more than 3 causes)	8 (10.7%)
Complex stocks	0

B.3 Model Equations

Arable Land = INTEG (arable land conversion rate, INITIAL ARABLE LAND)
Units: Ha
This stock represents the value of arable land. Arable land is used to produce plant products for food and other purposes. On an aggregated level and given the illustrative model purpose, I assume that arable land and area harvested have the same value. Due to the illustrative model purpose I also omit other land categories (e.g. settlement land, or water surfaces).

Arable land conversion rate = MIN((MIN(arable land demand, maximum arable land)-Arable Land)/ARABLE LAND CONVERSION TIME, Potential Arable Land/ARABLE LAND CONVERSION TIME)
Units: Ha/Year
This variable represents the net change from potential arable land into arable land. Its main driver is arable land demand. Arable land conversion can be limited either by the absence of potential arable land (that could be converted), or by the limited endowment of the agricultural sector (that results in a maximal area which can be cultivated by the current agricultural workforce).

ARABLE LAND CONVERSION TIME = 4
Units: Year
This constant represents the time it takes to convert forest, savannah and permanent meadows into arable land.

Arable land demand = Arable Land*(1+relative kcal gap)+Arable Land*(1+relative kcal gap)*ESTIMATED ARABLE LAND CONVERSION TIME*average population growth rate*SWITCH LAND ANTICIPATION
Units: Ha
This variable defines the demand for arable land by adjusting the current level to the food security status of the population. If there is a food surplus, arable land demand decreases. And if there is food scarcity, arable land demand increases. It is clear that land use change has many more and complex drivers (e.g. profitability of land use).

Here, on an aggregated level, I use one main driver that represents the physical needs of the population (given that many farmers mainly produce for subsistence). Conceptually this variable drives land use change and is founded in de Vries B. 2012. Sustainability Science. Cambridge University Press: Cambridge, UK.

Average population growth rate = TREND(population, OBSERVATION TIME SPAN, INITIAL POPULATION GROWTH RATE)
Units: Dmnl/Year
This variable calculates the average annual past trend of population growth.

DAYS PER YEAR = 365
Units: Day/Year
This constant represents the number of days per year.

Effect of output to input price ratio on share of income to fertilizer = WITH LOOKUP (relative output to input price ratio, ([(0,0)-(3,20)],(0,0),(0.956522,0),(1,1),(1.5,12.5),(1.6,14),(1.75,14.5),(1.9,14.9),(2,15),(2.5,15)))
Units: Dmnl
This variable contains the effect relationship between the fertilizer profitability indicator and the share of income spent on fertilizer purchase. (Similar to Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA. p.802ff).

Effect of soil organic matter on nutrient uptake = WITH LOOKUP (Soil Organic Matter,([(-10,0)-(200,1)],(-10,0.45),(0,0.45),(10,0.455),(20,0.46),(30,0.47),(40,0.48),(50,0.5),(60,0.525),(70,0.55),(80,0.575),(90,0.6),(100,0.635),(110,0.67),(120.186,0.711538),(130,0.75),(140,0.78),(150,0.81),(160,0.83),(170,0.84),(180,0.85),(190,0.85),(200,0.85)))
Units: Dmnl
Literature points out that nutrient uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent

the broader link from SOM to nutrient uptake I apply an effect relationship between SOM and the nutrient uptake with an upper and a lower bound. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

EQUILIBRIUM POPULATION = 1.552e+007
Units: Person
This constant represents the equilibrium population that equals the starting point of the population growth scenario.

ESTIMATED ARABLE LAND CONVERSION TIME = 4
Units: Year
This constant represents the estimated time need to convert potential arable land into arable land and equals the actual value (of the variable “arable land conversion time”). It is used to anticipate land use change to the needs of the population.

Exports of surplus production = MAX(0, food supply-food demand)
Units: Kcal/Year
This study seeks to analyze the potential of a country’s food production system to provide enough calories to the domestic population. Thus, trade is not the phenomenon of interest and in principle autarky is assumed. Only in the case of production surpluses the model assumes that surpluses are exported to other countries. This variable calculates the amount of calories that are exported each year.

Farm income = SMOOTHI(food price*production sold, FARM INCOME ADJUSTMENT TIME,INITIAL FARM INCOME)
Units: Rlc/Year
This variable calculates the aggregate farm income resulting from plant product sales

(in real local currency per year). Other sources of income are omitted due to the endogenous focus.

FARM INCOME ADJUSTMENT TIME = 1
Units: Year
This constant represents the time period between the production cycles, assuming that the farmers make one harvest per year.

Fertilizer application per hectare = fertilizer expenditure / FERTILIZER PRICE / Arable Land
Units: Ton/(Ha*Year)
This variable calculates the average amount of nutrient application per hectare, derived from the fertilizer expenditures, the given price and the area on which fertilizer is applied (arable land).

Fertilizer expenditure = farm income*share of income spent on fertilizer+FERTILIZER SUBSIDIES
Units: Rlc/Year
This variable adds private fertilizer expenditures and public fertilizer expenditures (fertilizer subsidies) to the total expenditures for fertilizer.

FERTILIZER PRICE = 351660
Units: Rlc/Ton
This constant represents the average fertilizer price in real local currency per ton.

FERTILIZER SUBSIDIES = 1.5e+010
Units: Rlc/Year
In Southeast Africa, courtiers typically have a policy program in place that subsidizes the purchase of fertilizer. These public programs can account for noteworthy parts of total fertilizer expenditure. Thus, this constant represents the public expenditure for fertilizer purchases (expressed in real local currency per year).

Food availability = PER CAPITA CONSUMPTION OF ANIMAL PRODUCTS+per capita consumption of plant products

Units: Kcal/(Person*Day)

This variable represents the amount of food that is available per person per day expressed in kilocalories. It represents the average of the total population and is used as a key indicator for measuring the food production system's performance.

Food demand = population*per capita kcal requirement plants*DAYS PER YEAR

Units: Kcal/Year

Food demand represents the total amount of plant-based food that the population requires in a whole year (expressed in calories). Demand is derived solely from the population and the population's requirement for vegetal food products. It is clear that there are many other factors affecting demand (such as income, price, social norms, consumption trends, etc.). Those additional factors were omitted in the light of the illustrative model purpose and because population is the main demand driver in fast growing societies such as Southeast African countries (Henrichsmeyer and Witzke, 1991). Source: Henrichsmeyer W., Witzke H.P. 1991. Agrarpolitik Band 1 Agrarökonomische Grundlagen; Eugen Ulmer GmbH & Co.: Stuttgart, Germany.

Food price = REFERENCE FOOD PRICE * (food supply / food demand)^ SENSITIVITY OF PRICE TO SUPPLY IMBALANCE

Units: Rlc/Kcal

This variable summarizes food prices. It changes according to changes in the supply-demand-ratio. Conceptually, this formulation is taken from Sterman (2000) and Meadows (1970). Sources: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA; Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Food supply = production*(1-WASTE AND NON FOOD USE SHARE OF PRODUCTION)

Units: Kcal/Year

This variable represents the amount of vegetal products that are available for consumption. It is derived from production, however, corrected for alternative, non-food uses of plant products.

INITIAL ARABLE LAND = 1.95323e+006
Units: Ha
This constant defines the initial value of the arable land stock.

INITIAL FARM INCOME = 1.02032e+011
Units: Rlc/Year
This constant defines the initial value of farm income.

INITIAL POPULATION GROWTH RATE = 0
Units: Dmnl/Year
This variable represents an estimate of the initial population growth rate trend. It is assumed to be 0 since the model starts in equilibrium condition (where population doesn't grow).

INITIAL POTENTIAL ARABLE LAND = 7.05906e+007
Units: Ha
This constant defines the initial value of the potential arable land stock.

INITIAL SOIL ORGANIC MATTER = 53.8765
Units: Ton/Ha
This constant defines the initial level of soil organic matter.

MAXIMAL AREA CULTIVABLE PER AGRICULTURAL WORKFORCE = 0.6
Units: Ha/Person
This constant represents the maximum productiveness of an agricultural workforce in terms of area coverage. It is assumed to be restricted by low endowment. A value around 0.6 hectares per person per year is realistic (Personal message from Dr. P. Nyanga, University of Zambia, Lusaka).

Maximum arable land = population*MAXIMAL AREA CULTIVABLE PER AGRICULTURAL WORKFORCE*SHARE OF AGRICULTURAL WORKFORCE ON POPULATION
Units: Ha

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

MAXIMUM INCOME SHARE TO FERTILIZER = 0.3
Units: Dmnl
This constant represents the maximum share of annual farm income spent on fertilizer purchase.

Mineralized nutrients from soil organic matter = soil organic matter mineralization rate*NUTRIENT CONTENT IN SOIL ORGANIC MATTER
Units: Ton/(Year*Ha)
Through the mineralization process of soil organic matter, nutrients are relieved and become available for the cultivated plants. This variable represents the amount of plant nutrients that are relieved through the mineralization process.

NUTRIENT CONTENT IN SOIL ORGANIC MATTER = 0.03
Units: Dmnl
This constant represents the share of plant nutrients that are contained in soil organic matter (such as nitrogen, phosphorus, potassium, etc.).

Nutrient uptake = effect of soil organic matter on nutrient uptake*(fertilizer application per hectare+mineralized nutrients from soil organic matter)
Units: Ton/(Ha*Year)
This variable represents the average amount of nutrients that is taken up by plants on one hectare throughout one growing season. Plants are not able to take up all mineralized nutrients available in the soil. Thus, this variable represents a fraction of the total mineralized nutrients (Schilling 2000). The uptake share of nutrients is assumed to depend on the level of soil organic matter (Johnston et al., 2009) and represented by the “effect of soil organic matter on nutrient uptake“. Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

OBSERVATION TIME SPAN = 5
Units: Year
This variable defines the time frame over which the past population growth rate is calculated.

ORGANIC MATTER ADDITION FROM INTERCROP INTERVENTION = 0.28
Units: Ton/Ha/Year
This constant represents the amount of organic matter that is additionally worked into the soil under the organic matter addition intervention.

ORGANIC MATTER FROM ANIMALS = 0.075
Units: Ton/Ha/Year
This constant represents the annual amount of organic matter applied through animal manure (per hectare arable land).

Organic matter input to soil = plant residues * SHARE OF PLANT RESIDUES REMAINING ON THE FIELD + ORGANIC MATTER FROM ANIMALS + STEP(ORGANIC MATTER ADDITION FROM INTERCROP INTERVENTION, STRAT TIME OF ORGANIC MATTER INTERVENTION)*SWITCH ORGANIC MATTER ADDITION
Units: Ton/(Ha*Year)
This variable represents the addition of organic material to the soil. Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production. In addition a policy can be activated constituting a third source of organic matter through intercropping.

PER CAPITA CONSUMPTION OF ANIMAL PRODUCTS = 132
Units: Kcal/Person/Day
Animal products account only for a small share of caloric intake in Southeast Africa. For this reason the model focuses on plant production and animal products are added for conceptual completeness. Thus, this constant represents the average amount of animal calories that a person consumes per day (e.g. calories from milk, meat and eggs).

Per capita consumption of plant products = MIN(food supply, food demand) / population / DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the amount of plant calories that are consumed on a daily and per capita basis. It either is equal to what a person wants to consume (food demand) in the case when food supply exceeds demand, or it is equal to what is available (supply) in cases when supply is lower than demand.

Per capita kcal requirement plants = PER CPITA KCAL REQUIREMENT-PER CAPITA CONSUMPTION OF ANIMAL PRODUCTS
Units: Kcal/(Person*Day)
This variable represents the required amount of calories coming from vegetal sources (per person per day).

PER CPITA KCAL REQUIREMENT = 2200
Units: Kcal/(Person*Day)
This variable represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organization of the United Nations (FAO) that calculates this parameter dependent on several population characteristics (e.g. age structure, level of physical activity, etc.). While the FAO value slightly changes over time, for simplicity, I assume a constant value of 2200 being realistic for the sub-Saharan Africa region.

Plant residues = WITH LOOKUP (yield, ([(-2e+006,0)-(3.2e+007,15)],(-3.07e+006, 0),(0,0),(307100,0.872664),(6.45e+006,3.44195),(3.1e+007,13.7191),(3.13e+007,13.7191)))
Units: Ton/Ha/Year
After harvesting, the main parts of a plant (yield) are removed from the field. However, there are other plant parts that remain on the field, the plant residues. Conceptually, this function is based in IPCC (2006). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Population = EQUILIBRIUM POPULATION*(1-SWITCH POPULATION) + Population Scenario*SWITCH POPULATION
Units: Person
This variable represents the country's total population and builds the main exogenous scenario. Malthusian theory states that the population level is dependent on food availability and thus would be endogenous to the model. By using population as an exogenous model input I do not want to challenge Malthusian theory. A link from food availability to population could potentially be implemented in the model (and was tested). However, population development is a complex phenomenon and depends on a host of other variables that are not represented in the model (physical and socio-economic ones). By implementing just the single link from food availability to population I would pretend a population study based on weak theoretical background and the study would loose its focus on food production system. Thus, I exclude this link and analyze how the system reacts to the exogenous input. Sensitivity tests revealed that varying the magnitude of population growth does not change the fundamental behavior patterns or mechanisms described in the article.

Population Scenario = INTEG (population scenario growth rate, EQUILIBRIUM POPULATION)
Units: Person
This stock is solely used to generate the (exogenous) population growth pattern and therefore cannot be considered as a model variable.

Population scenario fractional growth rate = RAMP(0.0025,5,25)+RAMP(
-0.00166667, 25,55)
Units: Dmnl/Year
This variable is solely used to generate the (exogenous) population growth pattern and therefore cannot be considered as a model variable.

Population scenario growth rate = Population Scenario*population scenario fractional growth rate
Units: Person/Year

This variable is solely used to generate the (exogenous) population growth pattern and therefore cannot be considered as a model variable.

Potential Arable Land = INTEG (-arable land conversion rate, INITIAL POTENTIAL ARABLE LAND)
Units: Ha
This stock represents the level of potential arable land including forest, savannah, pastures and permanent meadows. Under the given population scenario, arable land is not a limiting prdouction factor, assuming that there is a situation of abundant potential arable land. According to FAO data, this is the case for countries such as Zambia, Mozambique, or Zimbabwe (FAO, 2014). In other countries, such as Malawi, the situation is different because the land reserves that can be newly brought in production are almost exhausted. Sensitivity tests with the initial value of "potential arable land" revealed that the mechanisms described in the paper also hold, if land becomes a restrictive factor. However, as soon as the restriction kicks in, the system moves towards a productivity-centered mode of behavior that increases yields. Source: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

Production = Arable Land*yield
Units: Kcal/Year
This variable represents the annual domestic plant production. Note that the model assumes one harvest per year.

Production sold = production*SHARE OF PRODUCTION SOLD
Units: Kcal/Year
This variable represents the annual amount of plant products being sold at a market. In western countries this variable would typically be equal to the production. In the case of Southeast Africa, plant production is partly sold and partly self-consumed. Thus, this variable is only a fraction of the total production, and the producers consume the rest. Source: Chapoto A., Haggblade S., Hichaambwa M., Kabwe S., Longabaugh S., Sitko N., Tschirley D.2012. Agricultural Transformation in Zambia:

Alternative Institutional Models for Accelerating Agricultural Productivity Growth and Commercialization, IAPRI: Lusaka, Zambia.

REFERENCE FERTILIZER PRICE = INITIAL(FERTILIZER PRICE)
Units: Rlc/Ton
This constant stores the initial value of fertilizer price.

REFERENCE FOOD PRICE = 0.018
Units: Rlc/Kcal
This constant represents the reference food price (in real local currency per kcal) and simultaneously is the equilibrium food price.

REFERENCE SHARE INCOME TO FERTILIZER = 0.1
Units: Dmnl
This constant represents the reference share of annual farm income spent on fertilizer purchase.

Relative kcal gap = (per capita kcal requirement plants-per capita consumption of plant products)/per capita consumption of plant products
Units: Dmnl
This variable represents the gap between the requirement of plant products and the availability of plant products relative to available amount. The gap is zero if the required and the available amount are equal. If there is less vegetal food available than required the gap takes on a positive value, leading more arable land. If there is more vegetal food than required, the gap takes on a negative value, leading to less arable land.

Relative output to input price ratio = SMOOTHI((food price/REFERENCE FOOD PRICE)/(FERTILIZER PRICE/REFERENCE FERTILIZER PRICE), TIME TO PERCEIVE OUTPUT TO INPUT PRICE RATIO, (REFERENCE FOOD PRICE/REFERENCE FOOD PRICE)/(REFERENCE FERTILIZER PRICE/REFERENCE FERTILIZER PRICE))
Units: Dmnl

This variable represents the comparison of output and input prices relative to the initial value. It is used as a profitability indicator of fertilizer use (similar to the markup ratio of the indicated capacity utilization function in Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA. p.802ff).

SENSITIVITY OF PRICE TO SUPPLY IMBALANCE = -0.86
Units: Dmnl
This constant represents how sensitive the food price reacts to changes in respect to supply demand imbalances.

SHARE OF AGRICULTURAL WORKFORCE ON POPULATION = 0.241753
Units: Dmnl
This constant represents the share of people economically active in agriculture relative to the total population. The value was estimated from a data set from Zambia. Source: FAO. 2014. Food and Agriculture Organization. Population Estimates and Projections. Faostat.org, accessed: 20 November 2014.

Share of income spent on fertilizer = REFERENCE SHARE INCOME TO FERTILIZER*(1-SWITCH FERTILIZER MARKETS)+MIN(REFERENCE SHARE INCOME TO FERTILIZER*effect of output to input price ratio on share of income to fertilizer, MAXIMUM INCOME SHARE TO FERTILIZER)*SWITCH FERTILIZER MARKETS
Units: Dmnl
This variable represents the average share of the aggregated income that farmers spend on fertilizer. If fertilizer markets are assumed to be functioning the full formulation is active. If fertilizer markets are assumed to be dis-functional, this variable is equal to the reference share. Use the "switch fertilizer markets" variable to turn the structure on or off.

SHARE OF PLANT RESIDUES REMAINING ON THE FIELD = 0.5
Units: Dmnl
From the plant residues, only parts remain on the field and are worked into the soil. Others are eaten by animals, are used for building construction, are taken for energy

generation, etc. This constant represents the share of plant residues that actually remain on the field and are incorporated to the soil.

SHARE OF PRODUCTION SOLD = 0.45
Units: Dmnl
In a farming system that partly focuses on self-consumption, only parts of the production are sold at a market. This constant defines the share that is sold. It is clear that the share sold depends on many phenomena, such as food availability, profitability of sales, opportunity costs of self-consumption, etc. However, to focus on the core dynamics of the food production system I assume the share to be constant and exogenous. Sensitivity tests reveal that important model outcomes do not react sensitive to changes in the share sold, as long as the fertilizer policy is in place. Thus, the main conclusions and mechanisms described in the article also hold for changing shares of production sold.

Soil Organic Matter = INTEG (organic matter input to soil-soil organic matter mineralization rate, INITIAL SOIL ORGANIC MATTER)
Units: Ton/Ha
Soil organic matter (SOM) is an important soil component that accumulates through the addition of biomass to the soil. Soil microbes and creatures decompose SOM through the mineralization process (Scheffer and Schachtschabel, 2010). SOM levels are low in Southeast Africa (e.g. Tembo and Sitko, 2013). In the absence of time series, single measurements of soil organic matter levels on arable land are available and indicate levels between 35 and 90 tons organic matter per hectare. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Tembo S., Sitko N. 2013. Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Soil organic matter mineralization rate = Soil Organic Matter/SOIL ORGANIC MATTER MINERALIZATION TIME
Units: Ton/Ha/Year

This variable represents the mineralization process of soil organic matter (SOM). Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

SOIL ORGANIC MATTER MINERALIZATION TIME = 30
Units: Year
This constant represents the average soil stock residence time for organic matter. Parameter range: 10-50 years. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

STRAT TIME OF ORGANIC MATTER INTERVENTION = 5
Units: Year
This constant defines the time point when the organic matter addition intervention starts.

SWITCH FERTILIZER MARKETS = 0
Units: Dmnl
This is a switch variable for the fertilizer market effect. There is no effect of output-input price ratio on the share of income spent on fertilizer if the switch has the value 0 and there is an effect if the switch has the value 1. If fertilizer markets are functioning this switch should be put to 1. Otherwise to 0.

SWITCH LAND ANTICIPATION = 0
Units: Dmnl
This is a switch variable for the land anticipation policy. There is no anticipation if the switch has the value 0 and there is anticipation if the switch has the value 1.

SWITCH ORGANIC MATTER ADDITION = 0
Units: Dmnl

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

SWITCH POPULATION = 0
Units: Dmnl
This is a “switch variable” to choose between different exogenous model inputs. If the variable takes on the value 0, a constant population is applied. If the variable takes on the value 1, the exogenous population growth scenario is applied.

TIME TO PERCEIVE OUTPUT TO INPUT PRICE RATIO = 1
Units: Year
This variable represents the time it takes to perceive changes in the ratio between output and input prices (output prices are represented by vegetal food prices, input prices are represented by fertilizer prices).

WASTE AND NON FOOD USE SHARE OF PRODUCTION = 0.07
Units: Dmnl
This constant summarizes the share of plant production going into other uses than food. It includes seeds, animal fodder, waste and other use. The constant was estimated from FAO food balance sheets of Zambia (FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014).

Yield = YIELD PLATEAU*(1-10^(-YIELD RESPONSE COEFFICIENT*nutrient uptake))
Units: Kcal/(Ha*Year)
This variable represents the plant yield expressed in kcal per hectare per year. It is calculated using a Mitscherlich-Baule production function (Schilling 2000). For choosing a production function, many alternatives are available (e.g. square root functions, linear min-function, polynomic functions etc.). I chose a Mitscherlich-Baule production function because it is applicable on a large geographical and temporal scale, has empirical support and is adequate in complexity compared with

the rest of the model. Because factor endowment is low in SEA, a stage II function is acceptable (compared to a stage III function). Unlike the classical approach I calculate yield based on realized nutrient uptake instead of application rates. Source: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

YIELD PLATEAU = 2.7639e+007
Units: Kcal/Ha/Year
This constant is part of the Mitscherlich-Baule production function and represents the yield obtained under perfect factor availability.

YIELD RESPONSE COEFFICIENT = 2.5
Units: Ha*Year/Ton
This constant is part of the Mitscherlich-Baule production function that calculates yield. The constant is model specific and defines how yield reacts to changes in nutrient uptake.

Appendix C

Model Documentation Articles 3 and 4

C.1 Purpose and Scope of the Model

Articles 3 and 4 are based on non-cooperative Cournot market experiments that use a system dynamics simulation model as an interaction platform. Players' decisions were entered into the model platform and simulation outputs served as a base for subsequent decisions. Thus, the main purpose of the model was to enable this interaction and make farmers resemble their own farm. The model is based on the system dynamics model of article 1 with a few adjustments. The yield sector, soil organic matter sector, farm decision sector, and food availability sector were split into five parts that represent five farms – one farm for each player. Land and population were kept constant. And organic matter addition to the soil was made endogenous. The model was specified in Vensim software. During the experiments it was run in the gaming mode, which allowed to iteratively introducing the players' decisions to the interaction platform.

C.2 Summary Statistics of the Model

According to the Vensim software, the unit's within the model are consistent and the syntax is complete. The model was not sensitive to changes in values of the time step and integration methods.

The following summary statistics are based on the SDM-Doc tool that is available on the Systems Dynamics Society homepage (http://tools.systemdynamics.org/sdm-doc/; accessed: 25 April 2017).

Summary statistics of the model that underlies Articles 3 and 4

Model information	**Result**[1]
Total number of variables	183; 467
Total number of stocks	8 (4.4%); 32 (6.9%)
Total number of feedback loops Whereof reinforcing Whereof balancing	245 106 139
Total number of causal links	255; 939
Total number of macros	0
Variables with source information	0; 0
Dimensionless unit variables	55 (30.1%); 131 (28.1%)
Variables without predefined min or max value	179 (97.8%); 463 (99.1%)
Function sensitivity parameters	0; 0
Data lookup tables	0; 0
Time unit	Year
Initial time	2015
Final time	2050
Reported time interval	1
Time step	0.0625
Model is fully formulated	Yes
Warnings	**Result**
Number of undocumented variables	0; 0
Equations with embedded data	9 (4.9%); 21 (4.5%)
Variables not in any view	0; 0
Nonmonotonic lookup functions	0; 0
Cascading lookup functions	0; 0
Non-zero end sloped lookup functions	0; 0
Equations with if then else functions	0; 0
Equations with min or max functions	10 (5.5%); 38 (8.1%)
Equations with step pulse or related functions	0; 0
Potential Omissions	**Result**
Unused variables	0; 0
Supplementary variables	8 (4.4%); 36 (7.7%)
Supplementary variables being used	0; 0
Complex variables (more than 3 causes)	7 (3.8%); 19 (4.1%)
Complex stocks	0; 0

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[1] Excluding subscripts; including subscripts

C.3 Model Equations

C.3.1 Interface

Accumulated Maize Production Per Subject[farms] = INTEG (maize production per subject[farms], 0)
Units: Ton
This variable represents the pay-off function of the experiments (accumulated maize production of one subject).

Accumulated production in bags[farms] = Accumulated Maize Production Per Subject[farms]/BAG WEIGHT
Units: Bag
This variable represents the accumulated maize production expressed in common units for Zambian farmers (50 kg bags).

BAG WEIGHT = 0.05
Units: Ton/Bag
This constant represents a conversion factor between ton and 50 kg bags. (The latter is a common unit among Zambian smallholder farmers to express production related metrics).

Budget[farms] = farm expenditure for fertilizer and soil improvement[farms]
Units: Rlc/Year
This variable represents the budget available for fertilizer purchases and soil improvement on each farm (in real local currency).

Expenditure to fertilizer farm 1 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 1 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 2 = GAME (696)
Units: Rlc/Year

This variable captures and stores the decisions of farm 2 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 3 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 3 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 4 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 4 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 5 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 5 (the amount of money spent on fertilizer purchases).

Farm expenditure for fertilizer and soil improvement[farms] = MAX(SHARE OF INCOME TO FERTILIZER AND SOIL IMPROVEMENT,0)*farm income per subject[farms]
Units: Rlc/Year
This variable represents the budget available for fertilizer purchases and soil improvement on each farm (in real local currency).

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

LIMA PER HECTARE = 4
Units: Lima/Ha
Lima is a Zambian unit to measure area. This constant represents the conversion factor between hectares and lima.

Maize production per subject[farms] = maize production per farm type[farms]/scale factor from farm to subject
Units: Ton/Year
This variable represents the maize production per subject.

Maize yield[farms] = YIELD PLATEAU*effect of nitrogen on yield[farms]*effect of water on yield[farms]
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize grain harvested on one hectare). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

PRICE OF FERTILIZER BAG = 550
Units: Rlc/Bag
This constant represents the price that farmers pay for one bag of fertilizer. One bag weights 50kg and constitutes the "normal" commercial unit for fertilizer purchases.

Price per bag = producer price maize real*KG PER TON*BAG WEIGHT
Units: Rlc/Bag
This variable represents the maize price expressed in common units for Zambian farmers (real local currency per 50 kg bag).

Producer price maize real = REFERENCE PRODUCER PRICE MAIZE REAL * effect of supply and demand on producer price
Units: Rlc/Kg
This variable represents the producer price of maize (in real local currency per kilogram).

Production in bags[farms] = maize production per subject[farms]/BAG WEIGHT
Units: Bag/Year

This variable represents the maize production expressed in common units for Zambian farmers (50 kg bags per year).

Yield in bags[farms] = maize yield[farms]/BAG WEIGHT/LIMA PER HECTARE
Units: Bag/(Year*Lima)
This variable represents the maize yield expressed in common units for Zambian farmers (50 kg bags per lima per year).

C.3.2 Yield Sector

Above ground dry matter[farms] = plant residue above ground dry matter[farms]+yield maize dry matter[farms]
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production above ground (including all plant parts, also yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Bags of fertilizer purchased[farms] = total fertilizer expenditures real[farms]/PRICE OF FERTILIZER BAG
Units: Bag/Year
This variable represents the total amount of fertilizer bags that a subject purchases.

DRY MATTER FRACTON OF MAIZE YIELD = 0.87
Units: Dmnl
This constant represents the dry matter share of maize yields. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

EFFECT FACTOR OF NITROGEN ON YIELD = 4.03
Units: Ha*Year/Ton
This is a model and case specific constant in the Mitscherlich-Baule production function that calculates maize yields.

EFFECT FACTOR OF WATER ON YIELD = 0.004
Units: Year/Mm
This is a model and case specific constant in the Mitscherlich-Baule production function that calculates maize yields.

Effect intercept of soil organic matter on nitrogen[farms] = REFERENCE NITROGEN UPTAKE SHARE-INITIAL RELATIVE SOIL ORGANIC MATTER[farms]*EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Effect of nitrogen on yield[farms] = 1-10^(-EFFECT FACTOR OF NITROGEN ON YIELD*nitrogen uptake by maize[farms])
Units: Dmnl
This variable is part of the Mitscherlich-Baule production function that calculates maize yields.

Effect of water on yield[farms] = 1-10^(-EFFECT FACTOR OF WATER ON YIELD*water plant uptake[farms])
Units: Dmnl

This variable is part of the Mitscherlich-Baule production function that calculates maize yields.

EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN = 0.2
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER = 0.1
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. The model reacts rather sensitive to this parameter. A reality check in simulation outcomes suggests a value around 0.1. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Indicated nitrogen uptake share[farms] = EFFECT SLOPE OF SOIL ORGANIC MATTER ON NITROGEN*relative soil organic matter[farms]+effect intercept of soil organic matter on nitrogen[farms]
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Indicated water uptake share[farms] = relative soil organic matter[farms]*EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER+intercept of som effect on water[farms]
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

INITIAL RELATIVE SOIL ORGANIC MATTER[farms] = INITIAL(relative soil organic matter[farms])
Units: Dmnl
Literature points out that nitrogen uptake by plants is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Intercept of som effect on water[farms] = REFERENCE WATER UPTAKE SHARE-INITIAL RELATIVE SOIL ORGANIC MATTER[farms]*EFFECT SLOPE OF SOIL ORGANIC MATTER ON WATER
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet well researched (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

KG PER BAG = 50
Units: Kg/Bag
This constant defines the weight of one "bag" in kg.

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

MAIZE AREA PER SUBJECT = 2
Units: Ha
This constant defines the maize area of each subject. To ensure symmetry across farms, this constant is the same for all subjects.

Maize yield[farms] = YIELD PLATEAU*effect of nitrogen on yield[farms]*effect of water on yield[farms]
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize crenels harvested on one hectare). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). Source: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

MAXIMUM NITROGEN UPTAKE SHARE = 0.85
Units: Dmnl
Literature points out that pant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake a liner effect relationship between SOM and the nitrogen uptake share was applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Schilling (2000 p.435) indicates a nitrogen uptake of 65-85% in Europe. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J.,

Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

MAXIMUM WATER UPTAKE SHARE = 0.5
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Mineralized nitrogen[farms] = nitrogen fertilizer application per hectare maize[farms] + soil organic nitrogen mineralization rate[farms]
Units: Ton/(Year*Ha)
This variable represents the amount of mineralized nitrogen that is available in the soil. It includes nitrogen from organic and inorganic sources.

MINIMUM NITROGEN UPTAKE SHARE = 0.45
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, many of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake a liner effect relationship between SOM and the nitrogen uptake share was applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Schilling (2000 p.435)

indicates a nitrogen uptake of 65-85% in Europe. The lower bound is reduced here for the low SOM levels in Zambia. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany.

MINIMUM WATER UPTAKE SHARE = 0.05
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

NITROGEN CONTENT OF ABOVE GROUND RESIDUES = 0.006
Units: Dmnl
This constant is used to calculate the amount of plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter Chapter 11. Table 11.2. Page 11.17.

NITROGEN CONTENT OF BELOW GROUND RESIDUES = 0.007
Units: Dmnl
This constant is used to calculate the amount of plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

NITROGEN CONTENT OF FERTILIZER = 0.352
Units: Dmnl
This constant defines the share of nitrogen within a bag of fertilizer. Nitrogen concentrations in: Urea = 46%, Ammonium Nitrate = 33%, Ammonium Sulphate = 21%, Compound Fertilizers = 4-20%.

Nitrogen fertilizer application[farms] = bags of fertilizer purchased[farms] * NITROGEN CONTENT OF FERTILIZER*KG PER BAG/KG PER TON
Units: Ton/Year
This variable represents the annual total nitrogen fertilizer application.

Nitrogen fertilizer application per hectare maize[farms] = nitrogen fertilizer application[farms]/MAIZE AREA PER SUBJECT
Units: Ton/(Year*Ha)
This variable represents the per hectare annual, inorganic nitrogen fertilizer application on maize fields.

Nitrogen in plant residues below ground[farms] = plant residue below ground dry matter[farms]*NITROGEN CONTENT OF BELOW GROUND RESIDUES
Units: Ton/(Year*Ha)
This variable represents the total amount of nitrogen in plant residues that are below ground. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Nitrogen in plant residues above ground[farms] = plant residue above ground dry matter[farms]*NITROGEN CONTENT OF ABOVE GROUND RESIDUES
Units: Ton/(Year*Ha)
This variable represents the total amount of nitrogen in plant residues that are above ground. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

Nitrogen uptake by maize[farms] = mineralized nitrogen[farms]*uptake share of nitrogen[farms]

Units: Ton/(Year*Ha)
This variable represents the average amount of nitrogen that is taken up by maize plants on one hectare throughout one growing season. Maize plants are not able to take up all mineralized nitrogen available in the soil. Thus, this variable represents a share of the total mineralized nitrogen (Schilling 2000). The uptake share of nitrogen is assumed to depend on the level of soil organic matter (Johnston et al., 2009). Sources: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Per hectare expenditure for soil improvement[farms] = soil improvement expenditure real[farms]/MAIZE AREA PER SUBJECT
Units: Rlc/(Year*Ha)
This variable calculates the average money spent per hectare that is used to improve soil quality.

Plant residue above ground dry matter[farms] = PLANT RESIDUE ABOVE GROUND INTERCEPT+PLANT RESIDUE ABOVE GROUND SLOPE*yield maize dry matter[farms]
Units: Ton/(Year*Ha)
This variable represents the amount of residue dry matter production above ground (excluding yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. Note: units conversion Mg = Mega grams = 10^6g = 1t.

PLANT RESIDUE ABOVE GROUND INTERCEPT = 0.61
Units: Ton/(Year*Ha)
This constant is used to calculate the amount of plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-19%.

PLANT RESIDUE ABOVE GROUND SLOPE = 1.03
Units: Dmnl
This constant is used to calculate the amount of plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-3%.

Plant residue below ground dry matter[farms] = above ground dry matter[farms]*RATION BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production below ground (assumed that all is left in the soil as residues). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Page 11.14.

Plant uptake share of water[farms] = MIN(MAX(indicated water uptake share[farms],MINIMUM WATER UPTAKE SHARE), MAXIMUM WATER UPTAKE SHARE)
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

PRECIPITATION = 879
Units: Mm/Year
This constant represents the average, annual rainfall (based on Zambian data 1984-

2013). Under the assumption of a smallholder production system, precipitation is the main source of water for crop growth (because irrigation installations are expensive).

PRICE OF FERTILIZER BAG = 550
Units: Rlc/Bag
This constant represents the price that farmers pay for one bag of fertilizer. One bag weights 50kg and constitutes the "normal" commercial unit for fertilizer purchases.

RATION BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER = 0.22
Units: Dmnl
This constant is used to calculate the amount of plant residues. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. +-2s.d. as % of mean: +-26%.

REFERENCE NITROGEN UPTAKE SHARE = 0.5
Units: Dmnl
Literature points out that plant nitrogen uptake is a function of soil organic matter (SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

REFERENCE WATER UPTAKE SHARE = 0.1
Units: Dmnl
The share of water that is taken up by maize plants depends on the soil organic matter

content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely udnerstood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Relative soil organic matter[farms] = soil organic matter[farms]/INITIAL SOIL ORGANIC MATTER[farms]
Units: Dmnl
This variable represents the soil organic dry matter amount relative to its initial value.

Share of above ground plant residues incorporated to the field[farms] = WITH LOOKUP (per hectare expenditure for soil improvement[farms],([(-100,0)-(3267,3)],(-100,0.3),(0,0.3),(466.667,1),(1866.67,1.7),(2000,1.7)))
Units: Dmnl
This variable represents share of above ground plant residues that are incorporated into the field. It converts soil improvement expenditure into its effect in terms of incorporation of organic matter to the soil. The lookup table is estimated based on the costs of maize production. Source: Burke W.J., Hichaambwa M., Banda D., Jayne T.S. 2011. The Cost of Maize Production by Smallholder Farmers in Zambia. Working paper no. 50. FSRP, Lusaka, Zambia.

Soil improvement expenditure real[farms] = MAX(farm expenditure for fertilizer and soil improvement[farms]-indicated fertilizer expenditure[farms],0)
Units: Rlc/Year
This variable represents the amount of money that a farm spends on soil improvement (expressed in real local currency).

Soil organic nitrogen mineralization rate[farms] = Soil Organic Nitrogen[farms] / AVERAGE MINERALIZATION TIME

Units: Ton/(Year*Ha)

This variable represents the mineralization process of soil organic matter (SOM) and thus soil organic nitrogen. Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Total fertilizer expenditures real[farms] = fertilizer expenditure real[farms] + FERTILIZER SUBSIDIES/scale factor from total to subject

Units: Rlc/Year

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

Total nitrogen in plant residues[farms] = nitrogen in plant residues below ground[farms]+nitrogen in plant residues above ground[farms]

Units: Ton/(Year*Ha)

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

Total nitrogen in plant residues left on the field[farms] = MIN(total nitrogen in plant residues[farms], nitrogen in plant residues below ground[farms]+nitrogen in plant residues above ground[farms]*(share of above ground plant residues incorporated to the field[farms]))

Units: Ton/(Year*Ha)

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

Uptake share of nitrogen[farms] = MIN(MAX(indicated nitrogen uptake share[farms],MINIMUM NITROGEN UPTAKE SHARE), MAXIMUM NITROGEN UPTAKE SHARE)

Units: Dmnl

Literature points out that plant nitrogen uptake is a function of soil organic matter

(SOM, e.g. Johnston et al., 2009). Sources such as Oberholzer et al. (2014) even explicitly mention a POSITIVE FEEDBACK between SOM and yield. However, much of the interactions remain to be researched (Johnston et al., 2009). To represent the broader link from SOM to nitrogen uptake, a liner effect relationship between SOM and the nitrogen uptake share is applied with an upper and a lower bound. This variable is part of the formulation of this linear effect. Sources: Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101; Oberholzer H.R., Leifeld J., Mayer J. 2014. Changes in soil carbon and crop yield over 60 years in the Zurich Organic Fertilization Experiment, following land-use change from grassland to cropland. Journal of Plant Nutrition and Soil Science. 177, (5), 696-704.

Water plant uptake[farms] = PRECIPITATION*plant uptake share of water[farms]
Units: Mm/Year
The share of water that is taken up by maize plants depends on the soil organic matter content (SOM, e.g. Scheffer and Schachtschabel, 2010). Despite the existence of this linkage, its formal nature is not yet completely understood (Johnston et al., 2009). Here, the effect of SOM on water uptake is assumed to be linear with an upper and lower bound. This variable is part of this linear effect formulation. Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Johnston A.E., Poulton P.R., Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101.

Yield maize dry matter[farms] = maize yield[farms]*DRY MATTER FRACTON OF MAIZE YIELD
Units: Ton/(Year*Ha)
This variable represents the amount of dry matter in maize yields. Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17.

YIELD PLATEAU = 9
Units: Ton/(Ha*Year)
This constant is part of the Mitscherlich-Baule production function representing the maize yield under perfect factor availability. It assumes a mixture of maize varieties (hybrid and traditional seeds).

C.3.3 Soil Organic Matter Sector

Animal carbon per hectare = ANIMAL ORGANIC MATTER PER HECTARE * CARBON SHARE IN DRY MATTER
Units: Ton/(Ha*Year)
This variable represents the annual amount of organic carbon applied on arable land through animal manure.

ANIMAL ORGANIC MATTER PER HECTARE = 0.09
Units: Ton/(Ha*Year)
This constant represents the total annual amount of organic matter application through animal manure. Because animal production is not endogenously represented in the model, this variable is taken from FAO data. Source: calculated from FAO. 2014. Food and Agriculture Organization. Emission Series. Faostat.org, accessed: 11 November 2014.

ANIMAL ORGANIC NITROGEN PER HECTARE = 0.0085
Units: Ton/(Year*Ha)
This constant represents organic nitrogen application on arable land through animal manure. Because animal production is not endogenously represented in the model, this variable is taken from FAO data. Source: calculated from FAO. 2014. Food and Agriculture Organization. Emission Series. Faostat.org, accessed: 11 November 2014.

AVERAGE MINERALIZATION TIME = 31
Units: Year
This constant represents the average soil stock residence time for carbon and

nitrogen. Parameter range: 10-50 years. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Carbon in plant residues remaining on the field[farms] = plant residues remaining on the field[farms]*CARBON SHARE IN DRY MATTER
Units: Ton/(Ha*Year)
This variable represents the total amount of carbon contained in plant residues remaining on the field.

CARBON SHARE IN DRY MATTER = 0.58
Units: Dmnl
This constant represents the carbon share in soil organic dry matter. To convert C-content into soil organic mater (SOM), one can assume an average C-concentration of 58%. The C-concentration can vary from 40 to 60%. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Carbon to nitrogen ratio[farms] = Soil Organic Carbon[farms] / Soil Organic Nitrogen[farms]
Units: Dmnl
This variable represents C to N ratio in soil organic matter.

INITIAL SOIL ORGANIC CARBON = 20
Units: Ton/Ha
This constant represents the initial value of the soil organic carbon stock.

INITIAL SOIL ORGANIC MATTER[farms] = INITIAL(soil organic matter[farms])
Units: Ton/Ha
This variable represents the initial per hectare amount of organic dry matter on arable land.

INITIAL SOIL ORGANIC NITROGEN = 1.6
Units: Ton/Ha
This constant represents the initial value of the soil organic nitrogen stock.

NITROGEN FIXATION THROUGH SOIL BACTERIA = 0.03
Units: Ton/(Ha*Year)
This flow represents nitrogen fixation through free-living soil bacteria (excluding nodule bacteria from legumes). Scheffer and Schachtschabel (2010) p.402/403: normal input in Europe 1-30 kgN/ha/a, in the tropics up to 100 kgN/ha/a. Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Plant residue above ground dry matter[farms] = PLANT RESIDUE ABOVE GROUND INTERCEPT+PLANT RESIDUE ABOVE GROUND SLOPE*yield maize dry matter[farms]
Units: Ton/(Year*Ha)
This variable represents the amount of residue dry matter production above ground (excluding yield). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Table 11.2. Page 11.17. Note: units conversion Mg = Mega grams = 10^6g = 1t.

Plant residue below ground dry matter[farms] = above ground dry matter[farms] * RATION BELOW GROUND RESIDUE TO ABOVE GROUND DRY MATTER
Units: Ton/(Year*Ha)
This variable represents the total amount of dry matter production below ground (assumed that all is left in the soil as residues). Source: IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Chapter 11. Page 11.14.

Plant residues remaining on the field[farms] = plant residue above ground dry matter[farms]*(share of above ground plant residues incorporated to the field[farms]) + plant residue below ground dry matter[farms]
Units: Ton/(Ha*Year)

This variable represents the total amount of plant residues remaining on the field (accounting for below-ground residues and above-ground-residues).

Relative soil organic matter[farms] = soil organic matter[farms]/INITIAL SOIL ORGANIC MATTER[farms]
Units: Dmnl
This variable represents the soil organic dry matter amount relative to its initial value.

Share of above ground plant residues incorporated to the field[farms] = WITH LOOKUP (per hectare expenditure for soil improvement[farms],([(-100,0)-(3267,3)],(-100,0.3),(0,0.3),(466.667,1),(1866.67,1.7),(2000,1.7)))
Units: Dmnl
This variable represents share of above ground plant residues that are incorporates into the field. It converts soil improvement expenditure into its effect in terms of incorporation of organic matter to the soil. The lookup table is estimated based on the costs of maize production. Source: Source: Burke W.J., Hichaambwa M., Banda D., and Jayne T.S. 2011. The Cost of Maize Production by Smallholder Farmers in Zambia. Working paper no. 50. FSRP, Lusaka, Zambia.

Soil Organic Carbon[farms] = INTEG (soil organic carbon input[farms]-soil organic carbon mineralization rate[farms], INITIAL SOIL ORGANIC CARBON)
Units: Ton/Ha
Soil organic carbon is a major component of soil organic matter (SOM) and accumulates through the addition of biomass to the soil. Soil microbes and creatures decompose SOM through the mineralization process (Scheffer and Schachtschabel, 2010). SOM levels, and thus soil organic carbon levels are low in Zambia (e.g. Tembo and Sitko, 2013). In the absence of time series, single measurements of soil organic carbon levels on arable land are available and indicate levels between 20 and 50 tons carbon per hectare (e.g. Kaonga and Coleman, 2008). Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Tembo S., Sitko N. 2013. Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia,

Indaba Agriculture Policy Research Institute: Lusaka, Zambia; Kaonga M.L., Coleman K. 2008. Modeling soil organic carbon turnover in improved fallows in eastern Zambia using the RothC-26.3 model. Forest Ecology and Management. 256, (5), 1160-1166.

Soil organic carbon input[farms] = carbon in plant residues remaining on the field[farms]+animal carbon per hectare
Units: Ton/(Year*Ha)
This variable represents the addition of organic material to the soil (expressed in carbon units). Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production.

Soil organic carbon mineralization rate[farms] = Soil Organic Carbon[farms] / AVERAGE MINERALIZATION TIME
Units: Ton/(Year*Ha)
This variable represents the mineralization process of soil organic matter (SOM) and thus soil organic carbon. Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Soil organic matter[farms] = Soil Organic Carbon[farms]/CARBON SHARE IN DRY MATTER
Units: Ton/Ha
This variable represents the amount of organic dry matter in one hectare of arable land. "Soil organic matter (SOM) is probably the single component of the soil that has the greatest influence on the physical, chemical and biological properties of soils" (Shitumbanuma, 2013). SOM influences plant growth processes in manifold ways. An important contribution happens through the mineralization of nutrients that are captured in SOM (Scheffer and Schachtschabel, 2010; and Schilling, 2000). And another important contribution is the improvement of soil structure, nutrient, water

and energy retention capacity. For adequately representing SOM according to different functions we split SOM into two element components in this model (carbon and nitrogen). In Zambia SOM levels are low which results in low agricultural productivity (e.g. Tembo and Sitko, 2013). However, we did not find time series measuring SOM levels in Zambia (and most likely they do not exist). Sources: Shitumbanuma V., Chikuta, F. 2013. Nutrient Status of the Major Agricultural Soils of the Eastern Province of Zambia, The International Institute of Tropical Agriculture: Lusaka, Zambia; Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Tembo, S., Sitko, N. 2013. Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Soil Organic Nitrogen[farms] = INTEG (NITROGEN FIXATION THROUGH SOIL BACTERIA+soil organic nitrogen input[farms]-soil organic nitrogen mineralization rate[farms], INITIAL SOIL ORGANIC NITROGEN)
Units: Ton/Ha
Soil organic nitrogen is a major component of soil organic matter (SOM) and accumulates through the addition of biomass to the soil and soil bacteria fixating nitrogen from the air. Soil microbes and creatures decompose SOM through the mineralization process (Scheffer and Schachtschabel, 2010). Soil organic nitrogen that is mineralized serves as a nutrient for plant production (Schilling 2000). SOM levels, and thus soil organic nitrogen levels are low in Zambia (e.g. Tembo and Sitko, 2013). In the absence of time series, single measurements of soil organic nitrogen levels are available and indicate levels between 1.5 and 2 tons carbon per hectare (e.g. https://daac.ornl.gov). Sources: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany; Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; Tembo S., Sitko N. 2013. Technical Compendium:

Descriptive Agricultural Statistics and Analysis for Zambia, Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Soil organic nitrogen input[farms] = ANIMAL ORGANIC NITROGEN PER HECTARE+total nitrogen in plant residues left on the field[farms]
Units: Ton/(Ha*Year)
This variable represents the addition of organic material to the soil (expressed in nitrogen units). Two sources are captured: plant residues that remain on the field after harvest and organic matter from animal production.

Soil organic nitrogen mineralization rate[farms] = Soil Organic Nitrogen[farms] / AVERAGE MINERALIZATION TIME
Units: Ton/(Year*Ha)
This variable represents the mineralization process of soil organic matter (SOM) and thus soil organic nitrogen. Soil microbes and creatures decompose SOM. The decomposition process is proportional to the SOM level and can be captured by the equation above (Scheffer and Schachtschabel, 2010). Source: Scheffer F., Schachtschabel P. 2010. Lehrbuch der Bodenkunde. 16. Auflage ed., Spektrum Akademischer Verlag, Springer: Heidelberg, Germany.

Total nitrogen in plant residues left on the field[farms] = MIN(total nitrogen in plant residues[farms], nitrogen in plant residues below ground[farms]+nitrogen in plant residues above ground[farms]*(share of above ground plant residues incorporated to the field[farms]))
Units: Ton/(Year*Ha)
This variable represents the amount of nitrogen in plant residues left on the field after harvest.

C.3.4 Supply and Demand Sector

Accumulated Maize Production Per Subject[farms] = INTEG (maize production per subject[farms],0)
Units: Ton

This variable represents the pay-off function of the experiments (accumulated maize production of one subject).

AVERAGE DIETARY ENERGY REQUIREMENT = 2200
Units: Kcal/(Person*Day)
This variable represents the per capita Average Dietary Energy Requirement (ADER). The concept is taken from the Food and Agricultural Organization of the United Nations (FAO) that calculate this parameter dependent on several population characteristics (e.g. age structure, level of physical activity). While the FAO value slightly changes over time, for simplicity, we assume a constant value of 2200 being realistic for the case of Zambia.

Change in perceived supply demand balance = (supply demand balance-Perceived Supply Demand Balance)/TIME TO PERCEIVE SUPPLY DEMAND BALANCE
Units: Dmnl/Year
This variable represents change of the perception of the ratio between the potentially supplied and the demanded quantity of maize.

Consumer price maize = producer price maize real+VALUE ADDED
Units: Rlc/Kg
This variable represents the consumer price of maize (in real local currency per kilogram of maize). It is derived from the producer price by adding the value added (of subsequent actors in the value chain, including their costs).

Consumer price maize per ton = consumer price maize*KG PER TON
Units: Rlc/Ton
This variable represents the consumer price of maize (in real local currency per ton of maize).

DAYS PER YEAR = 365
Units: Day/Year
This constant represents the number of days per year (365).

Demand curve shift = indicated total maize consumption-REFERENCE FOOD MAIZE DEMAND

Units: Ton/Year

This variable represents shifts in maize demand due to changes in total population.

Demand curve slope = ELASTICITY REFERENCE INDUSTRY DEMAND * REFERENCE FOOD MAIZE DEMAND/REFERENCE CONSUMER PRICE MAIZE PER TON

Units: Ton*Ton/(Rlc*Year)

This variable represents the maize demand curve slope. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

Domestic maize consumption = MIN(domestic maize demand, potential domestic maize supply)

Units: Ton/Year

This variable represents the realized annual domestic maize consumption that is withdrawn from the inventories. If demand is higher than potential supply, this variable equals potential supply. And if potential supply is higher than demand, this variable equals demand.

Domestic maize demand = food maize demand+maize for non food use

Units: Ton/Year

This variable represents the total annual maize demand including food and non-food.

Effect of supply and demand on producer price = relative supply demand balance^SENSITIVITY OF PRICE TO SUPPLY DEMAND BALANCE

Units: Dmnl

This variable calculates the effect of a change in the perceived supply-demand ratio on the indicated producer price of maize. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

ELASTICITY REFERENCE INDUSTRY DEMAND = -0.1
Units: Dmnl
This variable indicates the price-quantity relationship on the maize demand curve. Because maize is the staple crop and plays a central role in the diet of Zambians, it is assumed to be inelastic. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

ENERGY SHARE OF MAIZE ON TOTAL DIET = 0.5
Units: Dmnl
This constant represents the intended share of kilocalories coming from maize compared to the total diet. Source: estimated from FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Exports in surplus situation = MAX(0,potential domestic maize supply-domestic maize demand-MAXIMUM DESIRED INVENTORY AS A SHARE OF DEMAND*domestic maize demand)
Units: Ton/Year
The model assumes that in cases of high inventory levels, surpluses are exported.

Food maize demand = MAX(0, REFERENCE FOOD MAIZE DEMAND+demand curve shift-demand curve slope*REFERENCE CONSUMER PRICE MAIZE PER TON+demand curve slope*consumer price maize per ton)
Units: Ton/Year
This variable represents the annual maize demand for food purposes.

Indicated total calory consumption = TOTAL POPULATION*AVERAGE DIETARY ENERGY REQUIREMENT*DAYS PER YEAR
Units: Kcal/Year
This variable represents the indicated annual food consumption of the total population in kilocalories.

Indicated total maize consumption = indicated total calory consumption*ENERGY SHARE OF MAIZE ON TOTAL DIET/(KCAL PER KG MAIZE*KG PER TON)

Units: Ton/Year

This variable represents the indicated annual maize consumption for food purposes in tons.

INITIAL MAIZE INVENTORY = 0

Units: Ton

This constant defines the initial value of maize inventories.

INITIAL PERCEIVED SUPPLY DEMAND BALANCE = 0.6

Units: Dmnl

This constant defines the initial supply to demand balance.

INVENTORY HANDLING TIME = 1

Units: Year

This constant represents the average inventory handling time.

KCAL PER KG MAIZE = 3071

Units: Kcal/Kg

This variable represents the number of kilocalories per kilogram maize. It is estimated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 20 November 2014).

KG PER TON = 1000

Units: Kg/Ton

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

Maize area per farm type[farms] = TOTAL MAIZE AREA/NUMBER OF FARMS

Units: Ha

This variable represents the area on which maize is produced per farm type.

MAIZE AREA PER SUBJECT = 2

Units: Ha

This constant defines the maize area of each subject.

Maize for non food use = maize for seed use+(SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER+SHARE OF MAIZE PRODUCTION WASTE)*potential domestic maize supply
Units: Ton/Year
This variable represents the annual maize demand for non-food purposes including seed, animal odder and food waste.

Maize for seed use = SUM(maize area per farm type[farms!])*SEED PER HECTARE
Units: Ton/Year
This variable represents the annual amount of maize used as seeds for planting the fields.

Maize Inventory = INTEG (maize production-domestic maize consumption-exports in surplus situation, INITIAL MAIZE INVENTORY)
Units: Ton
Unlike in classic microeconomic theory, this model allows for dis-equilibrium. If the demand is smaller than potential supply, surplus maize is stored in the inventory. Because the model addresses long-term phenomena, we are interested in the long-term development of the maize inventory (instead of seasonal changes). Thus, the present inventory stock captures the level just before the new maize harvest. The “normal” level is therefore zero. Only after years with surpluses the inventory starts to build up in this model. Conceptually the stock variable is taken from Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Maize production = SUM(maize production per farm type[farms!])
Units: Ton/Year
This variable represents the total maize production of the whole country.

Maize production per farm type[farms] = maize area per farm type[farms]*maize yield[farms]

Units: Ton/Year
This variable represents the amount of maize each farm type produces.

Maize production per subject[farms] = maize production per farm type[farms]/scale factor from farm to subject
Units: Ton/Year
This variable represents the maize production per subject.

Maize yield[farms] = YIELD PLATEAU*effect of nitrogen on yield[farms]*effect of water on yield[farms]
Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize crenels harvested on one hectare). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). Source: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

MAXIMUM DESIRED INVENTORY AS A SHARE OF DEMAND = 0.33
Units: Dmnl
This constant defines the maximal level of maize inventories that are kept as a fraction of current demand. In the case that the inventories surpass this level, the country exports maize.

NUMBER OF FARMS = 5
Units: Dmnl
This constant equals the number of subjects that participate in the experiments.

Perceived Supply Demand Balance = INTEG (change in perceived supply demand balance, INITIAL PERCEIVED SUPPLY DEMAND BALANCE)
Units: Dmnl
This stock represents the perception of the ratio between potentially supplied and demanded quantity of maize.

Potential domestic maize supply = maize production+Maize Inventory/INVENTORY HANDLING TIME

Units: Ton/Year

This variable represents the maize quantity that can be maximally supplied to the market. It includes the current production as well as production from previous years that are stored in maize inventories. Conceptually it is taken from Meadows D.L. 1970. Dynamics of commodity production cycles. Wright-Allen Press: Cambridge, MA, USA.

Producer price maize real = REFERENCE PRODUCER PRICE MAIZE REAL * effect of supply and demand on producer price

Units: Rlc/Kg

This variable represents the producer price of maize (in real local currency per kilogram).

REFERENCE CONSUMER PRICE MAIZE = INITIAL(consumer price maize)

Units: Rlc/Kg

This variable represents the reference consumer price per kilogram of maize in real local currency.

REFERENCE CONSUMER PRICE MAIZE PER TON = INITIAL(REFERENCE CONSUMER PRICE MAIZE*KG PER TON)

Units: Rlc/Ton

This variable represents the reference consumer price per ton of maize in real local currency. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

REFERENCE FOOD MAIZE DEMAND = INITIAL(indicated total maize consumption)

Units: Ton/Year

This variable represents the annual reference maize demand in tons. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

REFERENCE PRODUCER PRICE MAIZE REAL = 1
Units: Rlc/Kg
This constant represents the reference producer price of maize that is realized when supply and demand are in balance (in real local currency per kilogram).

REFERENCE SUPPLY DEMAND BALANCE = 1
Units: Dmnl
This constant represents the supply and demand balance if the market is in equilibrium (when supply equals demand).

Relative supply demand balance = Perceived Supply Demand Balance/REFERENCE SUPPLY DEMAND BALANCE
Units: Dmnl
This variable represents the relative state of the perceived ratio between the potentially supplied and the demanded quantity of maize compared to its initial value.

Scale factor from farm to subject = TOTAL MAIZE AREA/NUMBER OF FARMS/MAIZE AREA PER SUBJECT
Units: Dmnl
This is a scaling factor.

Scale factor from total to subject = NUMBER OF FARMS*scale factor from farm to subject
Units: Dmnl
This is a scaling factor.

SEED PER HECTARE = 0.03
Units: Ton/(Ha*Year)
This constant represents the amount of seed maize that is used to plant one average hectare. It was calculated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

SENSITIVITY OF PRICE TO SUPPLY DEMAND BALANCE = -0.86
Units: Dmnl

This constant determines how sensitive the producer price of maize reacts to changes in the perceived supply demand ratio. Conceptually this variable is based in: Sterman J.D. 2000. Business Dynamics. McGraw-Hill, Inc.: New York City, NY, USA.

SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER = 0.02
Units: Dmnl
This constant represents the share of total annual maize supply used to feed animals. It was calculated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

SHARE OF MAIZE PRODUCTION WASTE = 0.033
Units: Dmnl
This constant represents the share of total annual maize supply being lost and wasted. It was calculated from FAO data: FAO. 2014. Food and Agriculture Organization. Food Balance Sheet. Faostat.org, accessed: 11 November 2014.

Supply demand balance = potential domestic maize supply/domestic maize demand
Units: Dmnl
This variable represents the ratio between the potentially supplied and the demanded quantity of maize. Unlike in classic microeconomic theory, this model allows for dis-equilibrium. If the market is equilibrated (supply equals demand), then this variable takes on the value of 1. Otherwise it increases above or falls below 1.

TIME TO PERCEIVE SUPPLY DEMAND BALANCE = 0.3
Units: Year
This variable represents the time it takes to perceive changes in the ratio between potentially supplied and demanded quantity of maize.

TOTAL MAIZE AREA = 880000
Units: Ha
This constant represents the total area on which maize is produced. Note that one could separate the area planted with maize and the area harvested with maize, etc. For

simplicity it is assumed that they are equal and we call it “area harvested maize” (to make it clear that this area is relevant for calculating the maize production).

TOTAL POPULATION = 1.6e+007
Units: Person
This constant represents the total population.

VALUE ADDED = 1.7
Units: Rlc/Kg
This constant represents the value added of the maize value chain (from the farmer to the consumer).

C.3.5 Farm Decisions Sector

AGRICULTURAL POPULATION = 3.9e+006
Units: Person
This constant represents the number of people who work on farms throughout the whole country.

AVERAGE PER CAPITA INCOME FROM OTHER SOURCES THAN MAIZE = 400
Units: Rlc/Year/Person
This constant represents the per capita farm income from other sources than maize.

Change in perceived gross profit per hectare maize[farms] = (gross profit per hectare maize[farms]-Perceived Gross Profit Per Hectare Maize[farms])/TIME TO PERCEIVE PER HECTARE MAIZE GROSS PROFIT
Units: Rlc/(Year*Year*Ha)
This variable represents the change in perceived profit indicator of maize production.

Change in perceived maize availability[farms] = (maize availability per farm[farms]-Perceived Maize Availability[farms])/TIME TO PERCEIVE MAIZE AVAILABILITY

Units: Kcal/(Person*Day*Year)
This variable represents the change in farmers’ perception of maize availability.

Change of total farm income[farms] = (total farm income[farms]-Total Income Per Farm Type[farms])/TIME TO ADJUST FARM INCOME
Units: Rlc/(Year*Year)
This variable represents the change in farm income.

EFFECT OF MAIZE AVAILABILITY ON SHARE SOLD INTERCEPT = 0.055
Units: Dmnl
This constant is a parameter used to represent the farmers’ decision to sell maize depending on perceived maize availability.

EFFECT OF MAIZE AVAILABILITY ON SHARE SOLD SLOPE = 0.44
Units: Dmnl
This constant is a parameter used to represent the farmers’ decision to sell maize depending on perceived maize availability.

EFFECT OF MAIZE PROFITABILITY ON SHARE SOLD INTERCEPT = 0.0862
Units: Dmnl
This constant is a parameter used to represent the farmers’ decision to sell maize depending on perceived maize profitability

EFFECT OF MAIZE PROFITABILITY ON SHARE SOLD SLOPE = 0.328164
Units: Dmnl
This constant is a parameter used to represent the farmers’ decision to sell maize depending on perceived maize profitability.

Expenditure to fertilizer farm 1 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 1 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 2 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 2 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 3 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 3 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 4 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 4 (the amount of money spent on fertilizer purchases).

Expenditure to fertilizer farm 5 = GAME (696)
Units: Rlc/Year
This variable captures and stores the decisions of farm 5 (the amount of money spent on fertilizer purchases).

Farm expenditure for fertilizer and soil improvement[farms] = MAX(SHARE OF INCOME TO FERTILIZER AND SOIL IMPROVEMENT,0)*farm income per subject[farms]
Units: Rlc/Year
This variable represents the budget available for fertilizer purchases and soil improvement on each farm (in real local currency).

Farm income from other sources from maize = AGRICULTURAL POPULATION * AVERAGE PER CAPITA INCOME FROM OTHER SOURCES THAN MAIZE
Units: Rlc/Year
This variable represents the aggregated farm income of the total country with the exception of income generated thrugh maize sales.

Farm income from other sources than maize per farm = farm income from other sources from maize/NUMBER OF FARMS
Units: Rlc/Year
This variable represents the farm income from other sources than maize sales per farm type.

Farm income maize real[farms] = producer price maize real*sales maize[farms]*KG PER TON
Units: Rlc/Year
This variable represents the annual farm income received trough the sales of maize (in real local currency).

Farm income per subject[farms] = Total Income Per Farm Type[farms]/scale factor from farm to subject
Units: Rlc/Year
This variable represents the total farm income per subject.

Fertilizer expenditure real[farms] = MIN(farm expenditure for fertilizer and soil improvement[farms],indicated fertilizer expenditure[farms])
Units: Rlc/Year
This variable represents the amount of money that a farm spends on fertilizer purchases (expressed in real local currency).

FERTILIZER SUBSIDIES = 3.44e+008
Units: Rlc/Year
The government of Zambia subsidizes fertilizer use. This constant represents the level of subsides.

Gross profit per hectare maize[farms] = per hectare maize income[farms]-per hectare fertilizer expenditure[farms]-per hectare expenditure for soil improvement[farms]
Units: Rlc/(Year*Ha)
This variable represents a per area gross profit indicator of maize production. It uses the most important source of revenue and the two cost positions that are represented

in the experiment as a base for calculation. Source: Burke W.J., Hichaambwa M., Banda D., Jayne T. S. 2011. The Cost of Maize Production by Smallholder Farmers in Zambia, Food Security Research Project: Lusaka, Zambia.)

Indicated fertilizer expenditure[F1] = expenditure to fertilizer farm 1
Indicated fertilizer expenditure[F2] = expenditure to fertilizer farm 2
Indicated fertilizer expenditure[F3] = expenditure to fertilizer farm 3
Indicated fertilizer expenditure[F4] = expenditure to fertilizer farm 4
Indicated fertilizer expenditure[F5] = expenditure to fertilizer farm 5
Units: Rlc/Year
This variable unites each farm's fertilizer expenditure decision (in real local currency).

Indicated share of production sold from maize availability[farms] = EFFECT OF MAIZE AVAILABILITY ON SHARE SOLD INTERCEPT+EFFECT OF MAIZE AVAILABILITY ON SHARE SOLD SLOPE*relative perceived maize availability[farms]
Units: Dmnl
This variable represents the farmers' decision to sell maize depending on perceived maize availability. It is assumed to follow a positive linear relationship, meaning the more maize is available, the more are farmers willing to sell (e.g. a surplus). If maize is scarce farmers are assumed to be less willing to sell maize.

Indicated share of production sold from maize profitability[farms] = relative perceived gross profit per hectare maize[farms]*EFFECT OF MAIZE PROFITABILITY ON SHARE SOLD SLOPE+EFFECT OF MAIZE PROFITABILITY ON SHARE SOLD INTERCEPT
Units: Dmnl
This variable represents the farmers' decision to sell maize depending on perceived maize gross profitability. It is assumed to follow a positive linear relationship, meaning the more maize is profitable, the more farmers are willing to sell. If maize is less profitable, farmers are assumed to be less willing to sell maize.

INITIAL FARM INCOME = 2.45e+009

Units: Rlc/Year

This constant represents the initial annual aggregated farm income (in real local currency).

INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE = INITIAL(1500)

Units: Rlc/(Year*Ha)

This variable represents the initial level of the perceived per area gross profit indicator of maize production.

INITIAL PERCEIVED MAIZE AVAILABILITY = 650

Units: Kcal/(Person*Day)

This variable represents initial farmers' perception of maize availability.

KG PER TON = 1000

Units: Kg/Ton

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

MAIZE AREA PER SUBJECT = 2

Units: Ha

This constant defines the maize area of each subject.

Maize availability per farm[farms] = availability maize products*relative maize production to average[farms]

Units: Kcal/(Person*Day)

This variable represents maize availability per farm type.

Maize production per farm type[farms] = maize area per farm type[farms]*maize yield[farms]

Units: Ton/Year

This variable represents the amount of maize each farm type produces.

Maize yield[farms] = YIELD PLATEAU*effect of nitrogen on yield[farms]*effect of water on yield[farms]

Units: Ton/(Ha*Year)
This variable represents the maize yield (quantity of dried maize crenels harvested on one hectare). It is calculated using a Mitscherlich-Baule production function (Schilling 2000). Source: Schilling G. 2000. Pflanzenernährung und Düngung. Eugen Ulmer Verlag: Stuttgat, Germany; FAO. 2014. Food and Agriculture Organization: Production Series. Faostat.org, accessed: 11 November 2014.

NUMBER OF FARMS = 5
Units: Dmnl
This constant equals the number of subjects that participate in the experiments.

Per hectare expenditure for soil improvement[farms] = soil improvement expenditure real[farms]/MAIZE AREA PER SUBJECT
Units: Rlc/(Year*Ha)
This variable calculates the average money spent per hectare to improve soil quality.

Per hectare fertilizer expenditure[farms] = farm expenditure for fertilizer and soil improvement[farms]/MAIZE AREA PER SUBJECT
Units: Rlc/(Year*Ha)
This variable represents the annual per hectare fertilizer expenditure done by farmers (excluding subsidies).

Per hectare maize income[farms] = maize yield[farms]*producer price maize real * KG PER TON
Units: Rlc/(Year*Ha)
This variable represents the annual per hectare maize income by farmers. See: Varian H.R. 2007. Grundzüge der Mikroökonomik. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

Perceived Gross Profit Per Hectare Maize[farms] = INTEG (change in perceived gross profit per hectare maize[farms],INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE)
Units: Rlc/(Year*Ha)

This stock represents a perceived per area profit indicator of maize production. It is assumed that farmers make profitability-based decisions based on passed observations.

Perceived Maize Availability[farms] = INTEG (change in perceived maize availability[farms],INITIAL PERCEIVED MAIZE AVAILABILITY)
Units: Kcal/(Person*Day)
This stock represents the per capita maize availability situation perceived by farmers.

Producer price maize real = REFERENCE PRODUCER PRICE MAIZE REAL * effect of supply and demand on producer price
Units: Rlc/Kg
This variable represents the producer price of maize (in real local currency per kilogram).

Relative fertilizer expenditure[farms] = fertilizer expenditure real[farms] / farm expenditure for fertilizer and soil improvement[farms]
Units: Dmnl
This variable puts the fertilizer expenditure relative to the budget.

Relative perceived gross profit per hectare maize[farms] = Perceived Gross Profit Per Hectare Maize[farms]/INITIAL PERCEIVED GROSS PROFIT PER HECTARE MAIZE
Units: Dmnl
This variable represents the perceived per area profit indicator of maize production relative to its initial value.

Relative perceived maize availability[farms] = Perceived Maize Availability[farms] / INITIAL PERCEIVED MAIZE AVAILABILITY
Units: Dmnl
This variable represents the relative state of farmers’ perception of maize availability compared to the initial value.

RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION = 0.5
Units: Dmnl
This variable represents the weight farmers allocate to the profitability of maize relative to the availability of maize. Since both factors (food and cash) are essential, they are assumed to be equally important.

Sales maize[farms] = maize production per farm type[farms] * share of maize production sold[farms]
Units: Ton/Year
This variable represents the annual amount of maize being sold at a market. In western countries this variable would typically be equal to the production. In the case of Zambia, maize is partly sold and partly self-consumed. Thus, this variable is only a share of the total production, and the producers consume the rest. Source: Chapoto A., Haggblade S., Hichaambwa M., Kabwe S., Longabaugh S., Sitko N., Tschirley D. 2012. Agricultural Transformation in Zambia: Alternative Institutional Models for Accelerating Agricultural Productivity Growth and Commercialization, IAPRI: Lusaka, Zambia.

Scale factor from farm to subject = TOTAL MAIZE AREA/NUMBER OF FARMS / MAIZE AREA PER SUBJECT
Units: Dmnl
This is a scaling factor.

Scale factor from total to subject = NUMBER OF FARMS*scale factor from farm to subject
Units: Dmnl
This is a scaling factor.

SHARE OF INCOME TO FERTILIZER AND SOIL IMPROVEMENT = 0.25
Units: Dmnl
This constant represents the share of a farm's income that is available for fertilizer purchase and soil improvement. It was estimated based on an expenditure survey conducted among Zambian smallholder farmers.

Share of maize production sold[farms] = MIN(indicated share of production sold from maize profitability[farms]*RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION + indicated share of production sold from maize availability[farms]*(1-RELATIVE WEIGHT OF PROFITABILITY IN SALES DECISION), 1)
Units: Dmnl
This variable represents the share of the total production that is sold on a market. It is determined by two factors: the need for food and the need for cash. If there is enough maize, the share increases because farmers are assumed to have extra maize to sell and in a situation with maize scarcity, the share decreases because farmers are assumed to retain maize for self-consumption. On the other hand, if profits of maize production are high, farms are more likely to sell maize for earning cash.

Soil improvement expenditure real[farms] = MAX(farm expenditure for fertilizer and soil improvement[farms]-indicated fertilizer expenditure[farms],0)
Units: Rlc/Year
This variable represents the amount of money that a farm spends on soil improvement (expressed in real local currency).

TIME TO ADJUST FARM INCOME = 1
Units: Year
This constant represents the time between two growing seasons.

TIME TO PERCEIVE MAIZE AVAILABILITY = 0.3
Units: Year
This constant represents the time frame over which farmers perceive the maize availability situation.

TIME TO PERCEIVE PER HECTARE MAIZE GROSS PROFIT = 3
Units: Year
This constant represents the time horizon over which adjustment in profitability perception is made.

Total farm income[farms] = farm income from other sources than maize per farm + farm income maize real[farms]
Units: Rlc/Year
This variable represents the total farm income per farm type.

Total fertilizer expenditures real[farms] = fertilizer expenditure real[farms] + FERTILIZER SUBSIDIES/scale factor from total to subject
Units: Rlc/Year
This variable represents the annual fertilizer expenditure including private and public sources (in real local currency).

Total Income Per Farm Type[farms] = INTEG (change of total farm income[farms], INITIAL FARM INCOME/NUMBER OF FARMS)
Units: Rlc/Year
This stock represents the annual income per farm type after one year (being disposable to buy inputs for the following growing season, in real local currency).

C.3.6 Food Availability Sector

Availability maize products = per capita food maize availability kcal per year/DAYS PER YEAR
Units: Kcal/(Person*Day)
This variable represents the number of total kilocalories from maize products that are on average available per person per day.

Average maize production per farm = maize production/NUMBER OF FARMS
Units: Ton/Year
This variable calculates the average maize production per farm type.

DAYS PER YEAR = 365
Units: Day/Year
This constant represents the number of days per year (365).

Domestic maize consumption = MIN(domestic maize demand, potential domestic maize supply)
Units: Ton/Year
This variable represents the realized annual domestic maize consumption that is withdrawn from the inventories. If demand is higher than potential supply, this variable equals potential supply. And if potential supply is higher than demand, this variable equals demand.

KCAL PER KG MAIZE = 3071
Units: Kcal/Kg
This constant represents the number of kilocalories per kilogram maize. It is estimated from FAO data: FAO. 2014. Food and Agriculture Organization. Resource Series. Faostat.org, accessed: 20 November 2014.

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

Maize availability per farm[farms] = availability maize products*relative maize production to average[farms]
Units: Kcal/(Person*Day)
This variable represents maize availability per farm type.

Maize for non food use = maize for seed use+(SHARE OF MAIZE PRODUCTION TO ANIMAL FODDER+SHARE OF MAIZE PRODUCTION WASTE)*potential domestic maize supply
Units: Ton/Year
This variable represents the annual maize demand for non-food purposes including seed, animal odder and food waste.

Maize production = SUM(maize production per farm type[farms!])
Units: Ton/Year
This variable represents the total maize production of the whole country.

Maize production per farm type[farms] = maize area per farm type[farms]*maize yield[farms]
Units: Ton/Year
This variable represents the amount of maize each farm type produces.

NUMBER OF FARMS = 5
Units: Dmnl
This constant equals the number of subjects that participate in the experiments.

Per capita food maize availability kcal per year = total food maize availability in kcal/TOTAL POPULATION
Units: Kcal/(Year*Person)
This variable represents the total number of kilocalories from maize products that are available per person per year.

Relative maize production to average[farms] = maize production per farm type[farms]/average maize production per farm
Units: Dmnl
This variable indexes the current production per farm type to the average production.

Total food maize availability in kcal = total food maize availability in tons*KG PER TON*KCAL PER KG MAIZE
Units: Kcal/Year
This variable represents the total number of kilocalories from maize products that are available for human consumption per year.

Total food maize availability in tons = domestic maize consumption-maize for non food use
Units: Ton/Year
This variable represents the total number of tons from maize products that are available for human consumption per year.

TOTAL POPULATION = 1.6e+007

Units: Person

This constant represents the total population.