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

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Abstract

Food production systems in south-east Africa face a persistent puzzle: despite the implementation of numerous plausible food availability policies, the region's history is characterised by many cases of food production systems that have underperformed by not feeding the relevant population. This puzzle is addressed by investigating the dynamics of the region's food production systems. A theory-based framework is proposed to describe the interaction of biological and socio-economic processes that determine the availability of food calories. The framework is translated into a formal model and computer simulation used to analyse its dynamics in a population growth scenario together with different policy interventions. The results suggest three key concepts for understanding the performance of food production systems: stock management of soil organic matter, policy effort threshold, and land use anticipation. These concepts constitute theoretical approaches to explaining how dynamic interactions can create the puzzle of potentially beneficial policies failing to provide enough food calories.

Keywords: south-east Africa; food production systems; food availability; food policy; System Dynamics modelling

1. Introduction

Food production systems in south-east Africa persistently underperform, that is, they do not provide enough food for their growing populations. For example, in Zambia, Malawi, Mozambique, and Zimbabwe, food availability in general and the availability of average per capita calories in particular have been and (in some cases still are) insufficient (FAO, 2015). Agriculture plays an important role in south-east African economies,[1] and governments have implemented a numbers of food production policies to increase food availability for fast-growing populations (Mason, 2011; Chinsinga, 2012). Such policies have included input subsidies programmes, conservation agriculture, the use of legumes, and knowledge dissemination (e.g. MoA, 2011, p. 34).

A puzzle facing the food production systems is that policies, which have the plausible potential to ensure adequate levels of food availability, underperform. To be clear, this does not occur in all cases: for example, Dorward and Chirwa (2011) found that Malawi's fertiliser subsidy programme did contribute to increasing calorie availability per capita (Figure 1). However, in the same period, Zambia's fertiliser subsidy programme failed to provide enough food for the population. The situation has been similar for other policies, such as conservation agriculture (Giller *et al.*, 2009; Ngwira *et al.*, 2012; Thierfelder *et al.*, 2013). Plausible but unsuccessful food availability policies are not just a puzzle for researchers. Low food availability is a severe problem in south-east African countries (e.g. GFSI, 2015), and the respective governments spend considerable amounts of their state budget on agriculture: 4–29% in the period 2003–2010 (Chilonda *et al.* 2009; ONE 2013).[2]

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[1] Average shares of agriculture in gross domestic product (GDP) in the period 1991–2011 were 36% in Malawi, 29% in Mozambique, 17% in Zambia, and 17% in Zimbabwe (World Bank, 2016).

[2] Zambia 4–10%, Malawi 6–29%, Mozambique 4–6%, and Zimbabwe 6–12%

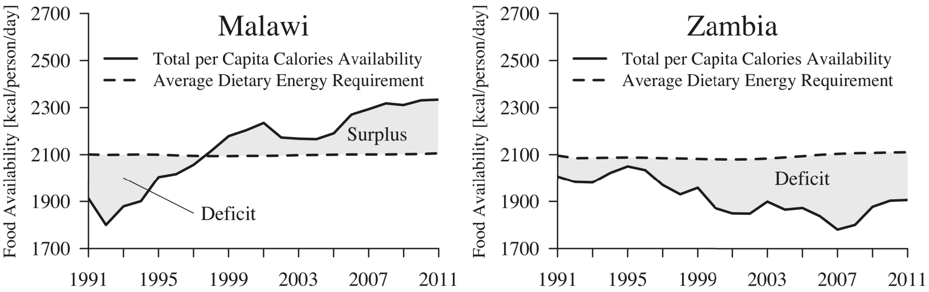

Figure 1: *Average daily calorie availability compared with the average dietary energy requirement for Malawi and Zambia (1991–2011) (Source: FAO 2015).*

The inability to resolve the puzzle posed by plausible but unsuccessful food production policies in south-east Africa has not resulted from a lack of data. Numerous case studies have been conducted and existing theories offer explanations as to why potentially beneficial policies have failed to improve food availability permanently. In the case of fertiliser input programmes, such explanations include crowding out effects in private markets (Xu *et al.*, 2009; Ricker-Gilbert *et al.*, 2011), implementation issues such as late provision of fertilisers (Tembo and Sitko, 2013), and dependence on international fertiliser prices (Dorward and Chirwa, 2011) (for an overview see Druilhe and Barreiro-Hurlé, 2012). To date, studies have typically focused on one policy in isolation. In addition, theories have been suggested for how the potential success of policies can be undermined by associated phenomena. The latter include low resource endowment and resource traps (Barrett, 2010), inadequate governance (e.g. Abbink *et al.*, 2011), and a higher rate of population growth than the rate of growth in food production (Henrichsmeyer and Witzke, 1991). However, despite the depth of existing policy research and numerous theories, potentially beneficial policies have varied in their performance in countries in south-east Africa, even when the characteristics of the countries' food and agricultural systems have been similar.

The central premise of this article is that the missing piece to the puzzle of food production policies is an appropriate research methodology for investigating the dynamic nature of the phenomena. Researchers have emphasised that the outcomes of food production systems are the result of complex dynamic processes (Ericksen, 2008), yet the human mind is not adapted to interpreting the behaviour of even low-order dynamic systems (Forrester, 1970). In acknowledging this limitation, researchers have developed integrated bio-economic models to investigate the interaction between the socio-economic and ecological elements of food production systems (for an overview see Brown, 2000). Many of these models focus on levels between farm and watershed and are conceptualised for time units of weeks and months. However, it is crucial to include an aggregate, long-term perspective in debates of policy intervention because food policies are parts of entire food production systems and some systems' processes play out over decades. Nevertheless, aggregated bio-economic models for systemic long-term analyses are scarce; exceptions include the models developed by Bach and Saeed (1992) and by Gerber (2016).

In this article, the food policy puzzle is addressed by filling the methodological gap. Unlike many bio-economic model-based studies that apply analogue models with high level of details, the simulation model developed here is an illustrative model (Morecroft, 2015, p. 444). Illustrative models represent feedback processes on aggregated levels and pay less attention to a detailed representation of low-level phenomena, thus allowing for identification, explanation, and analysis of fundamental modes of behaviour based on a generic system structure. The results of illustrative models typically include the identification of knowledge gaps, increased understanding of the endogenous interplay of the system's mechanisms, and the revealing of systemic leverage points that highlight strategic areas of policy intervention. This broad approach enables an overview and integration of different research fields, which is often not possible in studies that focus on detailed levels. However, the broad approach also comes at a cost: an illustrative model does not purport to fit a situation point-by-point and thus is not suitable to make predictions. Instead, it seeks to reveal the endogenous dynamics of a system. Furthermore, the aggregated nature of the approach is inappropriate for drawing conclusions on a detailed level (e.g. a specific case of policy design or implementation). Thus, the contribution of this article rests on a conceptual level, not on a detailed empirical level.

In common with Repenning (2002), this article does not report new data, demonstrate the existence of a new variable, or test the strength of a link between two variables. Instead, the principal contribution of this article is insights gained from established variables and relationships on an aggregated level from a long-term perspective for a hypothetical country, which results in explanations for the puzzle of plausible but unsuccessful food production policies. More specifically, the results reported here arose from two activities. First, theories were integrated into a framework that comprises key feedback processes determining the long-term dynamics of food production systems (based on Gerber, 2016). Second, an illustrative System Dynamics model was developed and analysed to characterise the range of behavioural outcomes that these feedback processes generate under a population growth scenario. These two activities resulted in concepts for understanding the performance of food production systems in south-east Africa.

The remainder of this article is structured as follows. After the presentation of the theoretical framework in the next section, the simulation model is specified by incorporating equations. Thereafter, selected simulation outcomes are presented and analysed. The concluding section elaborates on the emerging concepts and reflects on their theoretical and practical implications.

2. Theoretical framework

The theoretical framework was developed using causal loop diagramming and portrays a qualitative causal statement about a system's endogenous structure (Forrester, 1968; Lane, 2008). In illustrative model studies, such frameworks are generic and do not represent a specific study case. Instead, the same structure is applicable to different cases that mostly differ in their initial conditions and other parameter values. For this article, the theoretical framework (Figure 2) was used as a base to specify the simulation model.

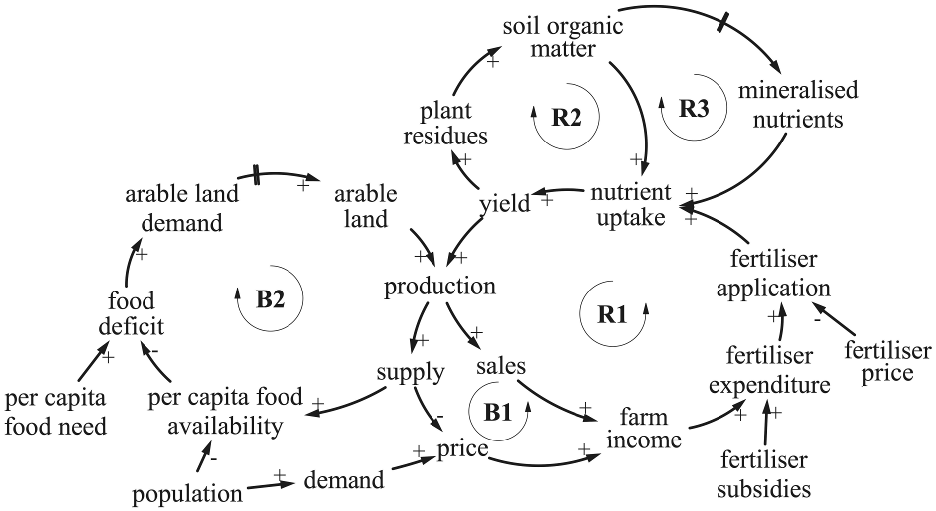

***Figure 2:** Theoretical framework for food production systems of plant products in south-east Africa. An arrow between two variables indicates a causal relationship directed towards the arrowhead. If the cause variable triggers a uniformly directed change in the effect variable, the link's polarity is labelled as 'positive' and shown as a plus (+). In the case of a reversely directed change, the link's polarity is labelled 'negative', and shown as a minus (-). Circular chains of causation add up to feedback loops. 'Reinforcing' feedback loops self-reinforce whatever behaviour is present, whereas 'balancing' feedback loops counteract the current behaviour for reaching a goal. R1 – reinforcing sales loop, R2 – reinforcing soil organic matter loop, R3 – reinforcing nutrient mineralisation loop, B1 – balancing yield loop, B2 – balancing land adjustment loop.*

To begin the analysis, a hypothetical country in south-east Africa was assumed to have a food production system that mainly produced plant-based food products. The country's agricultural sector focused on rain-fed crops, dominantly produced by low endowed smallholder farmers who consumed parts of their production. The hypothetical country had a growing population that demanded increasing amounts of food from its food production system. In order to analyse how internal structure generates behaviour, the environment of the food production system was assumed to remain sufficiently stable that the internal system's dynamics were not overrun by external influences.

The framework shown in Figure 2 builds on the causal loop diagram that is published Gerber (2016) and integrates theories that are crucial for the performance of food production systems. These theories relate to production (e.g. Heady and Dillon, 1961), soil dynamics (e.g. Scheffer and Schachtschabel, 2010), plant nutrition (e.g. Schilling, 2000), allocation decisions (e.g. Henrichsmeyer and Witzke, 1991; Varian, 2007), and commodity markets (e.g. Meadows, 1970). Many theories and concepts may initially seem oversimplified. For example, food availability is a central outcome of food production systems and its representation by average *per capita food availability* expressed in kcal per day is narrow. However, given the illustrative nature of the model, and given the importance of calories in food availability, *per capita food availability* serves as an approximation to food availability in this study. Hence, on closer inspection, the deliberate reduction of concepts and theories enables analysis of the endogenous interplay of larger systems, such as food production systems. Since a detailed description of the framework and its development has already been published in Gerber (2016), only a summary of the fundamental feedback loops is presented here.

A central concept in the framework is plant production, which is part of three feedback loops (B1, B2, and R1) (Figure 2). The balancing yield loop (B1) adjusts the supplied food quantity to the demanded food quantity. If low *production* leads to low *supply* (compared with *demand*), food *prices* will increase. As a result, *farm income*, *fertiliser expenditure*, *fertiliser application*, *nutrient uptake*, and plant *yield* will increase, which – all things being equal – will lead to a higher p*roduction* in the next growing season. While the B1 loop adjusts productivity (*yield*) to equilibrate markets, the reinforcing sales loop (R1) self-reinforces the current behaviour. If low *yields* cause low *production*, less surplus production will be available for *sales*, which will result in lower *farm income* and subsequently in lower *yields* in the next growing season. Depending on its direction, the R1 loop either augments or drains *yield*, *production*, and *farm income*. This self-reinforcing mechanism can be counteracted by the balancing B1 loop. In dynamic commodity modelling, the B1 loop is generally referred to as the ‘capacity utilisation loop’ (e.g. Sterman, 2000, p. 799), while the R1 loop is specific to systems with high shares of self-consumption.

The second determinant of *production* is *arable land* as part of the balancing land adjustment loop (B2, Figure 2). If *production* and *supply* are low, also *per capita food availability* will become low. As a consequence, *food deficit* will increase, which in turn will lead to higher *arable land demand* and with a conversion delay to more *arable land*. The B2 loop adjusts production to the physical needs of the population and in dynamic commodity modelling it is generally referred to as the ‘capacity acquisition loop’. The physical driver of land adjustment (*food deficit*) is chosen instead of purely economic indicators, due to the self-consumption orientation of south-east African smallholder farmers.

The remaining two feedback loops in Figure 2, the reinforcing soil organic matter loop (R2) and the reinforcing nutrient mineralisation loop (R3), are specific to plant-based food production systems and represent the role of soil fertility, using one of its important components – *soil organic matter* (SOM). As an externality of plant production, *plant residues* remain on the field and are partly worked into the SOM stocks. While SOM has an immediate effect on *nutrient uptake* (R2 loop), the mineralisation of SOM releases nutrients with a delay (R3 loop). Both loops reinforce whichever *yield* trajectory is present.

3. Model specification and key equations

The framework in Figure 2 is specified in a formal, mathematical simulation model. An overview of the stock and flow structure is presented in Figure 3 and key equations are presented in Table 1. The value and source of key parameters is listed in Table 2. Unlike other modelling approaches, in which it is crucial to find the ‘right’ value of a parameter (e.g. predictive modelling), the precise parameter value is of less relevance in an illustrative approach, such as the one presented here. Instead, it is crucial to estimate feasible parameter values and test whether changes still reveal the same modes of behaviour or whether there are fundamental changes in the system’s behaviour. Parameter estimation and sensitivity analysis were part of an iterative model validation process following Barlas (1996). Structure and behaviour-oriented validation tests were conducted throughout the modelling process, and their high number and qualitative nature mean that it is not possible to describe them further here. An example of interesting sensitivity analysis outcomes is presented in the Analysis section below. The full simulation model contains additional mechanisms for conceptual conclusiveness. It was specified using Vensim software and is available under supplementary materials.

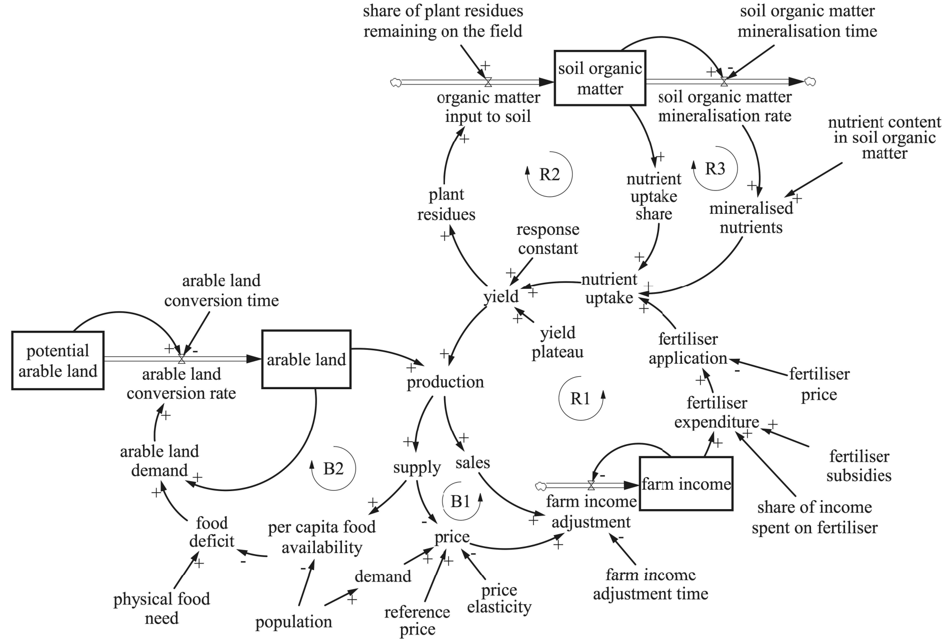

__Figure 3:__ Stock and flow diagram of the simulation model. A rectangle around a variable name indicates a stock variable that represents an accumulation process. The value of stock variables changes through flow variables that are represented by double-lined arrows flowing into and out of the stock rectangle.

Table 1: Key equations of the simulation model.

Equation number	Equation	New variables
1	$S = Prod = y \times AL$	S – supply Prod – production y – yield AL – arable land
2	$P = \left(\frac{S}{D}\right)^{\varepsilon} \times RefP$	P – price; D – demand ε – price elasticity RefP – reference price
3	$A = \frac{S}{Pop}$	A – per capita food availability Pop – population
4	$\frac{dAL}{dt} = \min\left(\frac{N - A}{A} \times AL, mCR(pAL)\right)$	N – physical food need mCR(pAL) – maximal conversion rate as a function of potential arable land
5	$y = ymax \times (1 - 10^{-C1 \times X1})$	ymax – yield plateau C1 – response constant X1 – nutrient uptake
6	$X1 = \left(\frac{FA}{AL} + \frac{SOM}{tmin} \times n\right) \times f(SOM)$	FA – fertiliser application SOM – soil organic matter tmin – mineralisation time n – nutrient content in SOM f(SOM) – nutrient uptake share as a function of SOM
7	$\frac{dSOM}{dt} = g(y) - \frac{SOM}{tmin}$	g(y) – plant residues worked into the soil as a function of y
8	$FA = \frac{(FI \times sf + FS)}{FP}$	FI – farm income sf – share of farm income spent on fertilizer FS – fertiliser subsidies FP – fertiliser price
9	$\frac{dFI}{dt} = P \times Sales(Prod) - FI$	Sales(Prod) – sales as a linear function of production

Table 2: *Key parameters and initial conditions of the simulation model (see Table 1 for an explanation of the parameters).*

Parameter	**Value**	**Source**
ε	-0.86 (dmnl*)	Gerber (2016)
RefP	0.018 (RealCurrency/kcal)	Estimated from Gerber (2016)
Pop	Not available, Scenario	See section headed 'Analysis'
N	2200 (kcal/person/day)	Estimated from FAO (2014-a)
ymax	2.8×10^7 (kcal/ha/year)	Estimated from Gerber (2016)
C1	2.5 (ha × year/ton)	Estimated from FAO (2014-b, maize in Zambia)
tmin	30 (year)	Scheffer and Schachtschabel (2010)
n	0.03 (dmnl)	Scheffer and Schachtschabel (2010)
sf	0.1 (dmnl)	Estimated from Gerber (2016)
FS	1.5×10^{10} (RealCurreny/year)	Estimated from Government of the Republic of Zambia (2014), Howard *et al.* (1993), Chiwele *et al.* (2010), Zulu *et al.* (2000)
FP	3.5×10^5 (RealCurreny/ton)	Estimated from MAOC (2014)
Initial SOM	54 (ton/ha)	Estimated from Scheffer and Schachtschabel (2010)
Initial AL	1.95×10^6 (ha)	Estimated from FAO (2014-c, Zambia)
Initial Potential AL	7.06×10^7 (ha)	Estimated from FAO (2014-c, Zambia)

Notes: *dmnl – dimensionless

4. Analysis

To characterise the range of behaviour that the food production system produces and to understand the impact of parameters and policy interventions, the model has been extensively analysed. To highlight some of the model's interesting dynamics, a subset of experiments are presented in this section. The analysis was structured as shown in Figure 4a: an exogenous population growth scenario and different interventions were applied to the food production system of a hypothetical country. The analysis revealed how the system performed in terms of food availability under these exogenous changes. The variable 'per capita food availability' was chosen as a key indicator of food availability because it was a central outcome of the food production system and target of many policy interventions. For simplicity, the population's diet was considered sufficient if 2200 or more kcal per capita per day were available (FAO, 2014-a).

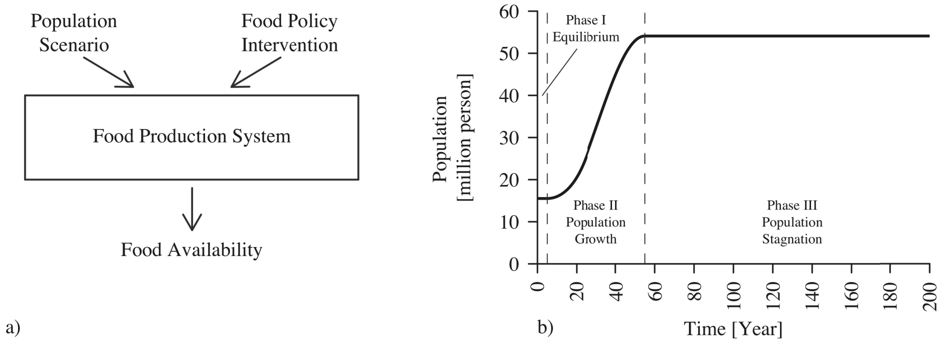

Figure 4: *Exogenous assumptions of the analysis: a) Analysis design, b) Exogenous population scenario.*

The exogenous population scenario served as a premise for the analysis and represented a demographic transition in three phases: Phase I – an equilibrium phase with adequate food availability for 15.2 million people from year 0 to year 5, Phase II – a growth phase in which the population grew for 50 years from the initial level in year 5 to 54.2 million people in year 55, and Phase III – a stagnation phase in which the population staid at the year 55 level until year 200 (Figure 4b). The equilibrium assumption in Phase I was not realistic from an empirical point of view, but it allowed for analysis of the impact of one change at a time. Currently, south-east Africa populations are in the growth phase (II), and Phase III was set to 145 years in order to investigate the long-term steady-state behaviour of the system.

It is important to re-emphasise that the study neither attempted to make point predictions at any future date nor it propose the view that all external forces of food production systems in south-east Africa would stay constant for the next 200 years. Instead, the article aimed to understand fundamental system properties under a time horizon that was long enough for long-term food production system processes to unfold (e.g. soil dynamics). Additionally, it is important to acknowledge that a population is a complex phenomenon that depends on many physical and socio-economic factors, one of which is food availability. Potentially, the link from food availability to population could have been implemented. However, this link would have meant shifting the focus of the present article from food production systems to populations and would have meant that the model was driven by additional exogenous assumptions. Therefore this link was excluded and it was analysed how the food production system reacted to the exogenous population scenario.

Table 3: *Overview of the experiments and assumptions about intervention areas.*

Strategic area of intervention	**Experiment 1**	**Experiment 2**	**Experiment 3**	**Experiment 4**	**Experiment 5**	**Foundation and model assumptions**
Functioning input markets	–	x	–	x	x	Fertiliser markets in south-east Africa are disfunctional in terms of access to cash, information, and input goods (Druilhe and Barreiro-Hurlé, 2012). To compensate for these shortcomings, a fertiliser allocation mechanism following market principles is introduced after year 5.
Additional legumes in cultivation schemes	–	–	x	x	x	Soil organic matter levels are low in south-east Africa. The legume interventions will address this shortcoming, assuming that from year 5 onwards 20% of arable land is cultivated with, for example, legumes as intercrops and fallow crops.
Land use anticipation	–	–	–	–	x	This intervention assumes that arable land is converted in accordance with the predicted demands of a future population (instead of reacting to the current population's land demands).

Notes: x symbol – scenario included in the experiment, – symbol –scenario excluded from the experiment

To analyse the food production system, different strategic areas of intervention and their combinations were tested in experiments. An overview of the experiments is presented in Table 3. Sensitivity and scenario analyses served as tools to test the relevance of uncertainty in parameter values. The results revealed that the mechanisms were robust in different population and land availability scenarios, and in parameter changes in a feasible range.

Three simulation experiments provided a useful introduction to important system properties. Experiment 1 tested how the food production system reacted to the population scenario without any additional intervention. Experiment 2 was identical to the first experiment, except that farmers allocated fertiliser according to an expected profitability indicator (indexed output to input price ratio, conceptually similar to Sterman, 2000, pp. 802–805). This mechanism assumes that current failures which affect fertiliser markets - such as inadequate access to cash, lack of information, and physical unavailability of fertilizer - are removed (Druilhe and Barreiro-Hurlé, 2012). Experiment 3 was identical to Experiment 1, except that farmers used more legumes in their cropping scheme. Figure 5 shows the trajectory of per capita food availability for all three experiments.

Experiments 1–3 performed identically through the equilibrium phase (years 0–5). Through the population growth phase (years 5–55), they shared a similar pattern, with decreasing food availability when the population grew rapidly and increasing food availability towards year 55 when the rate of population growth slowed down. Compared with the benchmark of 2200 kcal, all three experiments underperformed during this period. As the population grew, food demand increased, and the food production system adjusted food supplies through the two adjustment mechanisms – the balancing yield loop (B1 loop, Figure 2) and the balancing land adjustment loop (B2 loop). However, the results of Experiment 1 revealed that the adjustment capacity of the two loops was limited, resulting in the lowest availability of calories in the three experiments. The B2 loop was constrained due to farm endowment restrictions and the limitations of the B1 loop were addressed in the other two experiments (Experiments 2 and 3). In Experiment 2, the fertiliser market intervention immediately strengthened the adjustment capacity of the B1 loop and food availability increased, which reduced the pressure to increase arable land through the

B2 loop. However, the adjustment was too weak to reach adequate food availability in the population growth phase. In Experiment 3, the legume intervention indirectly strengthened the B1 loop through SOM, which accumulated with a delay. As a result, the food production system initially adjusted through the B2 loop by increasing arable land, which led to low food availability, similar to that in Experiment 1. Only when both stocks, SOM and arable land, were increased and the population growth had slowed down, food availability in Experiment 3 increased and surpassed food availability in Experiment 2. In the phase of population stagnation after year 55, food availability fell and started to stabilise at around 1600 kcal in Experiment 1, while it stabilised around 2150 kcal in Experiments 2 and 3.

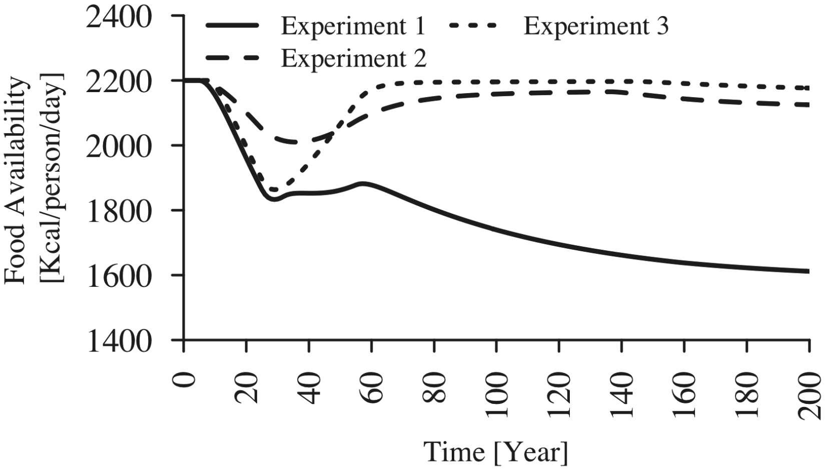

Figure 5: *Simulation results of food availability in Experiment 1 (no intervention), Experiment 2 (functioning fertilizer markets) and Experiment 3 (use of legumes).*

The simulation results shown in Figure 5 highlight two important characteristics of the food production system's behaviour. First, even if the applied intervention areas addressed current failures in the system and even if they were implemented appropriately, taken in isolation they were not able to ensure adequate food availability during the population growth phase. Second, both interventions considerably improved food availability in the post-population growth phase compared with Experiment 1, in which none of the system's failures was addressed.

For a deeper understanding of the source of the different behaviours in Figure 5, it was helpful to analyse the SOM stocks and recall that they were part of reinforcing soil loops (R2 and R3 loops). Since the processes were self-reinforcing in nature, they amplified whichever behaviour currently dominated. In Experiment 1, decreasing yields led to decreasing SOM stock levels, which in turn led to further decreases in yields. This created a vicious cycle, until external forces such as the B1 loop stabilised the SOM stocks (Figure 6). In the other two experiments (Experiments 2 and 3), SOM stock levels stabilised at higher levels than in Experiment 1. The increased stock levels strengthened the B1 loop and had an increasing effect on yield, production, and food availability. Thus, a first key finding in understanding the performance of food production systems was that that SOM stocks played a crucial role in food availability and that they could be managed by interventions.

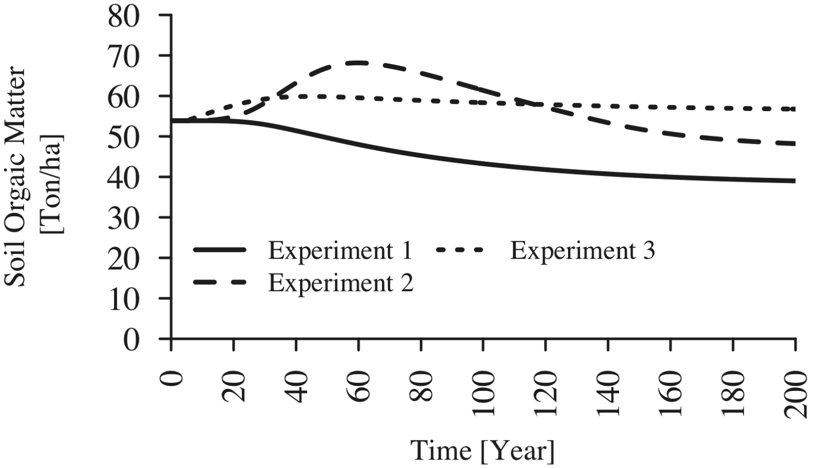

Figure 6: *Simulation results for soil organic matter in Experiments 1-3.*

Given that the management of the soil fertility stocks was crucial for the food production system’s performance and that the two analysed interventions were beneficial but still underperformed, this raised the question of how they worked in combination. Figure 7 shows the results of Experiments 1–3 as well as Experiment 4, which combined the fertiliser market intervention with the legume intervention. The simulation results suggested that that food availability was insufficient during the population growth phase. While the combination of the interventions initially increased food availability, it then performed worse than the legume intervention in isolation (Experiment 3). This was a surprising result in terms of dynamics because combined interventions erode the benefits of a single intervention. Further analysis showed that the combined interventions strengthened the B1 loop (even more than the interventions in isolation) and therefore removed additional adjustment pressure from the B2 loop. However, as shown in Experiment 3, the development of arable land was a crucial element for reaching adequate food availability in the population growth phase. Thus, a second key finding in understanding food production systems' performance was that the systemic interplay of combined interventions could offset the benefits of a single intervention.

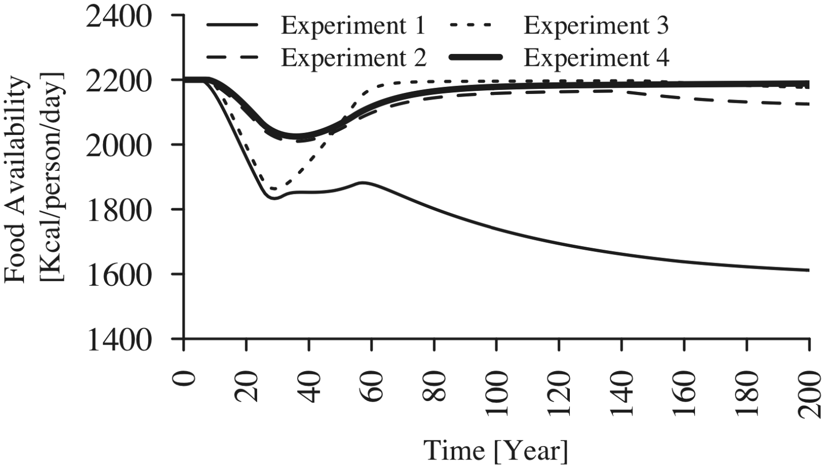

***Figure** 7: Simulation results of food availability in Experiments 1- 3, and 4 (functioning fertilizer markets and use of legumes).*

Two interesting phenomena are noteworthy, given the importance of land development. First, arable land started to increase later in Experiment 4 than in previous experiments. Second, actual arable land lagged behind the demand for arable land due to the delay in converting potential arable land into cultivable farmland (Figure 8). Because the arable land demand of a fast growing population increased rapidly, the delay in arable land catching up with the demanded level of food production became severe. Thus, a third key finding in understanding food production systems' performance is that there is a stock management problem associated with arable land.

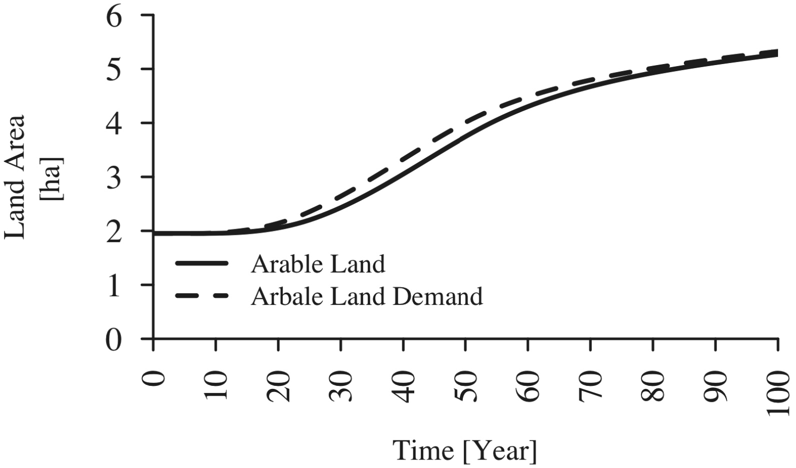

Figure 8: *Simulation results of arable land and arable land demand during the transition period (years 0–100) in Experiment 4.*

To overcome the land management problem, a fifth experiment was conducted to add a mechanism to the setting of the fourth experiment. The central idea of Experiment 5 was to anticipate future needs of arable land, instead of just reacting to current demands. A mechanism was introduced into the model, which assumed that actors would estimate the future population growth rate by assuming it would be equal to the average of the five last years. Arable land demand would then become a function not only of the current demand, but also of the current demand adjusted for expected future population growth. The fertiliser markets and legume interventions were kept in Experiment 5, as in Experiment 4.

Figure 9 shows the simulation results for Experiments 4 and 5, and they suggest that the newly introduced mechanism considerably improved food availability during the population growth phase. Although the mechanism implemented to project population growth initially underestimated and later overestimated the actual growth rate (and thus still caused some fluctuations), the results were much closer to the caloric goal of 2200 kcal.

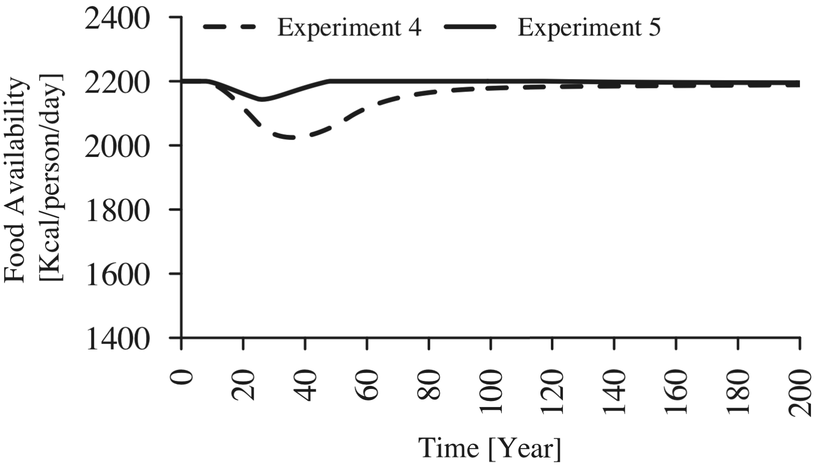

Figure 9: *Simulation results of food availability in Experiments 4 and 5 (functioning fertilizer markets, use of legumes, and land anticipation).*

The interventions analysed and tested to date were formulated using feasible parameter values. However, the values are uncertain and may vary from case to case. Figure 10 shows a more comprehensive set of simulations, in which the area covered with legumes per year and the farmer's response to fertiliser profitability are varied. Food availability is shown statically for the last year of the population growth phase (year 55). The results highlight that several parameter combinations result in the same availability of calories and increasing parameter values lead to increasing food availability. Food availability becomes saturated with increasing parameter values, but its response to increasing intervention parameters is non-linear. This is especially the case for the fertiliser market intervention, which in isolation is saturated below the targeted 2200 kcal per capita (lowest line in Figure 10). Thus, if the interventions are implemented at different intensities, or with varying implementation efforts, their success in terms of food availability will vary.

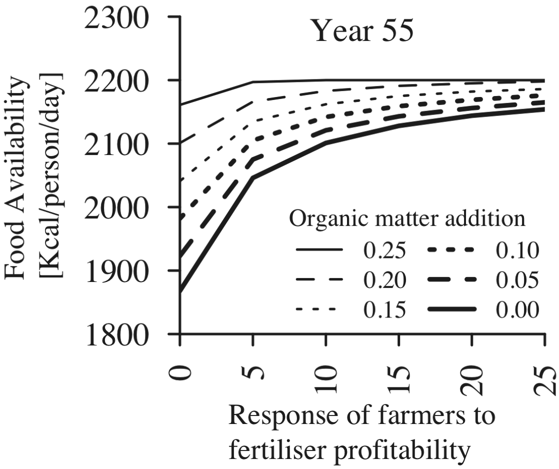

Figure 10: *Simulation results of food availability in year 55 for varying intervention intensities of legume use (organic matter addition) and functioning input markets (response of farmers to fertiliser profitability).*

To summarise, the results of the five experiments presented above provide a number of interesting insights into food production systems. First, they indicate that systems without additional interventions will not have sufficient adjustment capacity to feed a growing population due to limitations in yield and land adjustment mechanisms (B1 and B2 loops, Figure 2). Second, the insufficient adjustment capacity could be improved by interventions such as functioning input markets, increased use of legumes in the crop rotation scheme and anticipation of land development. However, combined interventions can offset the benefits of a single intervention due to their systemic interaction, as revealed by the combined input market and legume interventions in Experiment 4. Third, SOM stock management is a leverage point for lasting increases in yields and indirectly strengthening the B1 loop. Fourth, the performance of an intervention depends on the effort put into the intervention. The results shown in Figure 10 suggest that there are thresholds of efforts above which the interventions work effectively enough to break vicious cycles. If interventions are implemented below the threshold, long-term food availability will still be higher than in the no-intervention scenario, but below the target of 2200 pc kcal. Fifth, there is a stock management problem connected to arable land during phases of rapid population growth. The increasing food demand partly translates into increasing demand for arable land. However, the land conversion process delays arable land development compared with the arable land demand. Therefore, actual arable land is always below its demanded level, resulting in a food deficit. A possible solution is to anticipate population growth and to ensure that arable land is available on time.

5. Discussion and Conclusions

In south-east Africa, population growth poses a challenge to food production systems which aim to achieve sufficient levels of food availability. In this context, south-east African countries face a puzzle of food policies that are potentially beneficial but still do not succeed in providing enough food for the people. Based on established theories and links, a system dynamics model was developed and analysed to gain insights into this puzzle and the food production systems' performance. Three concepts help crystallise the outcomes and capture their implications for understanding the dynamics of food production systems in south-east Africa.

5.1 Management of soil organic matter stocks

Soil organic matter (SOM) is important in food production systems because it is a dynamic leverage point and has the possibility of accumulating over time. Problems associated with low SOM stock levels, such as low productivity, have been discussed in the literature (e.g. Kumwenda *et al.*, 1997). Nevertheless, understanding and considering the dynamic nature of SOM are still not standard practice in soil studies, in which key concepts such as 'dynamic equilibrium' are sometimes overlooked (Johnston *et al.*, 2009). Framing SOM as a stock and recognising the associated stock management problem allows for basic insights in terms of dynamics: stock levels change according to the inflows and outflows to the stock (Gerber, 2016). Thus, SOM levels decease as long as the inflow to the stock (addition of organic matter) is lower than the outflow of the stock (mineralisation rate of organic matter). This is the case even when a policy is applied that, in theory, should be beneficial for SOM. It is not enough merely to introduce the policy in order to reverse the decreasing dynamics.

However, the policy needs to add sufficient organic matter to the stock so that the inflow becomes larger than the outflow. Thus, a farmer confronted with low SOM levels should try to increase soil fertility by adding organic matter at a faster rate than SOM is mineralised.

The findings of this illustrative modelling approach suggest that SOM dynamics are crucial not only in soil studies but also from a broader systemic perspective, and thus the dynamic nature of SOM should receive special attention in both research and policy formulation. Empirical approaches such as long-term field trials might support the investigation of structural properties of SOM dynamics. To test the impact of concrete policies, detailed modelling approaches might be necessary.

5.2 Land use anticipation

Despite numerous studies that have investigated the effect of land use change on several variables, no authors have addressed the problem of delayed land adjustment. However, as suggested by the results of the analysis in this article, delayed land adjustment is a feasible hypothesis to explain why food production systems recurrently underperform in feeding rapidly growing populations. Thus, the anticipation of land use change is an option that should be considered and investigated further in countries with considerable land reserves (e.g. Zambia and Zimbabwe).

It should be pointed out that such land development comes at environmental costs (e.g. greenhouse gas emissions and loss of biodiversity) and there is a trade-off between food availability and environmental welfare outcomes. Hence, the findings presented here are reliable from a systemic perspective under the assumption that the conversion of land happens regardless. With regards to practicality, how such an anticipation of land conversion could be implemented on a policy level is not straightforward, especially since the adaptation from reactive to anticipatory planning implies a major change of paradigm, both on government level and farm level. Thus, as indicated by this illustrative modelling, the strategic land anticipation approach might need to be complemented by approaches that are more detailed, in order to substantiate policy formulation and implementation.

5.3 Policy effort threshold

The results of the analysis highlight a basic but important fact: implementing a policy does not guarantee success, even when policies are implemented appropriately. Conceptually separating the effort threshold from inherent failures opens up for explanations of success or failure of food availability policies. Consider, for example, the cases of Zambia and Malawi. Both countries have implemented similar policy programmes, with similar reported drawbacks (e.g. Xu *et al.*, 2009; Ricker-Gilbert *et al.*, 2011; Druilhe and Barreiro-Hurlé, 2012). Therefore, these drawbacks cannot explain the difference in success (Malawi) and failure (Zambia) in terms of providing enough calories. However, the concept of effort threshold does offer a hypothesis which differentiates between the two cases: Malawi puts relatively more resources into agricultural policies than Zambia and therefore succeeds in produce enough calories for its population.

In addition, the success of a single policy depends on other policies being in place and their non-linear dynamic interaction. As shown in Experiment 4, one policy might offset benefits of another policy and the lack of success cannot be attributed to an intrinsic lack in one of the policies, but needs to be attributed to their systemic interaction. Hence, there are consequences for researchers, since many recent studies of south-east Africa have focused on analysing single polices or even isolated effects of single policies, and might have missed important interaction phenomena with other interventions. While it is important to understand single policies, it can be equally important to understand how their benefits can be undermined or enhanced through systemic interactions. For policymakers, this implies that the effort thresholds of policies shift with the addition or removal of other policies.

5.4 Further implications

The results of the systemic analysis have highlighted concepts that contribute to explaining the food policy puzzle in south-east Africa and have implications for food systems research. Combining relatively simple theories results in multiple feedback mechanisms, time delays, and non-linear relationships, and can create behaviours that are difficult to understand intuitively. In this article, an illustrative System Dynamics model was developed and simulated to show that the dynamic interaction of the theories is not yet fully understood but may lead to new insights and a deeper understanding of food production systems.

Future work could build on this analysis in a number of ways. First, specifying a formal model, makes explicit the elements of the aggregated framework that would normally be implicit in a partial, segregated approach. Thus, the model developed here should be easier to challenge and improve. Present feedback mechanisms can be refined or extended based on further theories or alternative theories. Second, food availability strategies could be analysed in greater depth in terms of their interactions, potential synergies, and trade-offs. Modelling a case country might offer valuable insights into the concrete application of the proposed theories and how they create the food policy puzzle. Third, this analysis demonstrates that illustrative dynamic feedback-based models are useful tools for improving the understanding of food production systems on a country level. A country facing food deficits holds two major strands of strategies to increase food availability without importing food: increase the food production area and increase productivity. Both strategies comprise a stock management problem. Anticipation of land demand is the key to providing sufficient food within the area-increase strategy. In the productivity-strategy, soil organic matter (SOM) stocks play a key role in improving the food production system’s performance. Additionally, policy interventions face effort thresholds. If interventions are implemented with little effort (e.g. a small budget and implementation failures) policies will fall below the threshold and fail to provide enough food. However, the interventions will succeed if they are implemented above the threshold. Such systemic insights demonstrate the importance of approaches, such as System Dynamics, that enable the integration of different research fields.

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Literature

Abbink K, Jayne TS, Moller LCM. 2011. The relevance of a rules-based maize marketing policy: An experimental case study of Zambia. *Journal of Development Studies* **47**(2): 207-230.

Bach NL, Saeed K. 1992. Food self-sufficiency in Vietnam: A search for a viable solution. *System Dynamics Review* **8**(2): 129-148.

Barlas Y. 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review* **12**(3): 183-210.

Barrett CB. 2010. Smallholder market participation: Concepts and evidences from Eastern and Southern Africa. In: *Food Security in Africa – Market and Trade Policy for Staple Foods in Eastern and Southern Africa*, Sarris A, Morrison J (eds). FAO and Adward Elgar: Cheltenham, UK; 41-76.

Brown DR. 2000. *A Review of Bio-economic Models*. Cornell African Food Security and Natural Resource Management Program (AFSNRM). http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.200.8771&rep=rep1&type=pdf [3 November 2014].

Chilonda P, Olubode-Awosola O, Minde I. 2009. *Monitoring of Public spending in Agriculture in Southern Africa*. Southern Africa Regional Strategic Analysis and Knowledge Support: Pretoria, South Africa. Issues Brief No. 8.

Chinsinga B. 2012. *The Political Economy of Agricultural Policy Processes in Malawi: A Case Study of the Fertilizer Subsidy Programme*. Working Paper 39. Future Agricultures Consortium: Brighton, UK.

Chiwele D, Fowler M, Humphrey E, Hurrell A, Willis J. 2010. *Agriculture Case Study: Evaluation of Budget Support in Zambia*. Oxford Policy Management: Oxford, UK.

Dorward A, Chirwa E. 2011. The Malawi agricultural input subsidy programme: 2005/06 to 2008/09. *International Journal of Agricultural Sustainability* **9**(1): 232-247.

Druilhe Z, Barreiro-Hurlé J. 2012. *Fertilizer Subsidies in sub-Saharan Africa*. ESA Working Paper 12-04FAO, Agricultural Development Economics Division: Rome, Italy.

Ericksen PJ. 2008. Conceptualizing food systems for global environmental change research. *Global Environmental Change* **18**(1): 234-245.

FAO. 2015. *Food Balance Sheet*. http://faostat.fao.org/site/368/default.aspx - ancor [15 April 2015].

FAO. 2014-a. Food and Agriculture Organisation. Food Security Indicators. http://www.fao.org/faostat/en/ - data/FS [24 November 2014].

FAO. 2014-b. Food and Agriculture Organisation. Production Series. http://faostat.fao.org/site/567/default.aspx - ancor [11 November 2014].

FAO. 2014-c. Food and Agriculture Organisation. Ressource Series. http://faostat.fao.org/site/674/default.aspx [20 November 2014].

Forrester JW. 1968. Market growth as influenced by capital investment. *Industrial Management Review* **9**(2): 83-105.

Forrester JW. 1970. Counterintuitive behaviour of social systems. In: *Collected Papers of Jay W Forrester (1975 collection)*. Wright-Allen Press: Cambridge, MA; 211-244.

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.

GFSI. 2015. *The Global Food Security Index*. http://foodsecurityindex.eiu.com [8 May 2015].

Giller KE, Witter E, Corbeels M, Tittonell P. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* **114**(1): 23-34.

Government of the Republic of Zambia. 2014. *Estimates of Revenue and Expenditure: Including Capital and Constitutional and Statutory Expenditure*. Government of the Republic of Zambia: Lusaka, Zambia.

Heady EO, Dillon JL. 1961. *Agricultural Production Functions*. Iowa State University Press: Ames, IA.

Henrichsmeyer W, Witzke HP. 1991. *Agrarpolitik.* Band: 1 *Agrarökonomische Grundlagen*. Eugen Ulmer GmbH & Co: Stuttgart, Germany.

Howard JA, Chitalu GM, Kalonge SM. 1993. *The Impact of Investments in Maize Research and Dissemination in Zambia. Part One: Main Report*. Michigan State University: EastLansing, MI.

Johnston AE, Poulton PR, Coleman K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy* **101**: 1–57.

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB, Blackie MJ. 1997. Soil fertility management in Southern Africa. In *Africa's Emerging Maize Revolutaion*, Byerlee D, Eicher CE (eds). Lynne Rienner: Boulder, CO; 157-172.

Lane DC. 2008. The emergence and use of diagramming in system dynamics: a critical account. *Systems Research and Behavioral Science* **25**(1): 3-23.

MAOC. 2014. *Provincial Prices from 1994 to 2012*. Ministry of Agriculture and Cooperatives: Lusaka, Zambia.

Mason NM. 2011. Marketing Boards, Fertilizer Subsidies, Prices, & Smallholder Behavior: Modeling & Policy Implications for Zambia [Dissertation]. Michigan State University: Michigan.

Meadows DL. 1970. *Dynamics of Commodity Production Cycles*. Wright-Allen Press: Cambridge, MA.

MoA. 2011. *Malawi Agricultural Sector Wide Approach. A Prioritised and Harmonised Agricultural Development Agenda: 2011–2015*. Government of Malawi, Ministry of Agriculture and Food Security: Lilongwe, Malawi.

Morecroft JDW. 2015. *Strategic Modelling and Business Dynamics: A Feedback Systems Approach*. 2nd ed. John Wiley & Sons: Chichester, UK.

Ngwira AR, Aune JB, Mkwinda S. 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research* **132**: 149-157.

ONE. 2013. *The Maputo Commitments and the 2014 African Union Year of Agriculture*. https://s3.amazonaws.com/one.org/images/131008_ONE_Maputo_FINAL.pdf [22 December 2016].

Repenning NP. 2002. A simulation-based approach to understanding the dynamics of innovation implemenatation. *Organization Science* **13**(2): 109-127.

Ricker-Gilbert J, Jayne TS, Chirwa E. 2011. Subsidies and crowding out: A double-hurdle model of fertilizer demand in Malawi. *American Journal of Agricultural Economics* **93**(1): 1-17.

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: Stuttgart, Germany.

Sterman JD. 2000. *Business Dynamics*. McGraw-Hill: New York.

Tembo S, Sitko N. 2013. *Technical Compendium: Descriptive Agricultural Statistics and Analysis for Zambia*. Indaba Agriculture Policy Research Institute: Lusaka, Zambia.

Thierfelder C, Chisui JL, Gama M, Cheesman S, Jere ZD, Bunderson WT, Eash NS, Rusinamhodzi L. 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. *Field Crops Research* **142**: 47-57.

Varian HR. 2007. *Grundzüge der Mikroökonomik*. Oldenbourg Wissenschaftsverlag GmbH: Munich, Germany.

World Bank. 2016. *World Development Indicators*. http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators&preview=on [16 November 2016].

Xu Z, Burke WJ, Jayne TS, Govereh J. 2009. Do input subsidy programs ‘crowd in’ or ‘crowd out’ commercial market development? Modeling fertilizer demand in a two-channel marketing system. *Agricultural Economics* **40**(1): 79-94.

Zulu B, Nijhoff JJ, Jayne TS, Negassa A. 2000. *Is the Glass Half-empty or Half Full? An Analysis of Agricultural Production Trends in Zambia*. Food Security Reserach Project: Lusaka, Zambia.