Agricultural Theory in System Dynamics

A Case Study from Zambia

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Abstract

Global population growth and its food demand put increasing pressure on natural resources such as arable land and soil fertility. This paper uses Zambia as a study case to analyse the dynamics between food security, agriculture and natural resources. The country's challenge is huge: its growing population already now suffers from chronic food insecurity while the low endowment agriculture works on depleted soils. To evaluate different policy areas a bio-economic system dynamics model is developed integrating agronomic and agricultural economic theory. The theoretical model is specified and calibrated for the maize system in Zambia. Simulations show that the current input and food reserve policies are short-term oriented and costly. Focusing instead on the use and building up of natural resources allows for higher long-term food availability and increases the resilience of the food system. The paper therefore suggests a shift of the policy focus away from public food reserves towards an enhancement of natural resources.

Key Words*: Bio-Economic Model, Food Security, Low Endowment Agriculture, Natural Resources, System Dynamics, Theory Building, Zambia*

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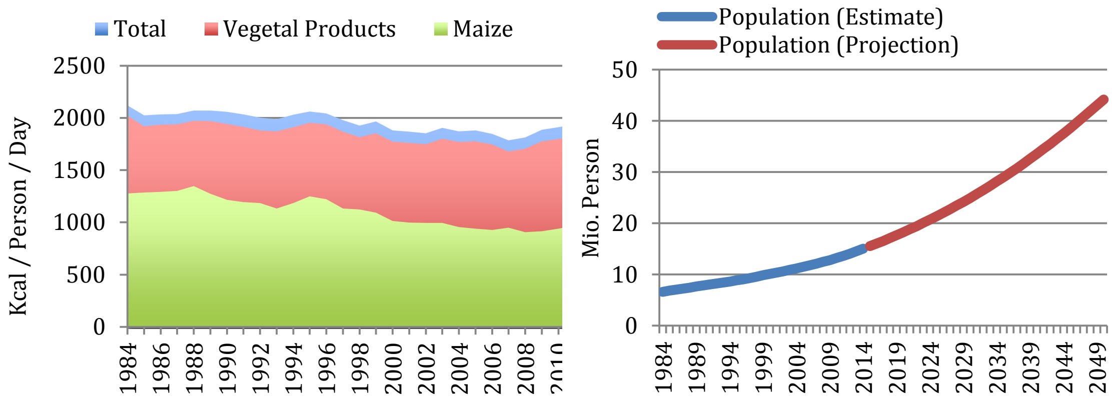
Introduction

The globally growing population puts high demands on both agriculture and natural resources (Foley et al., 2011). A major challenge in this area is to enhance food security without compromising natural resources (Ericksen et al., 2010). To analyse such systemic challenges, integrated bio-economic models have been used to investigate the interaction of social, economic and ecological aspects of food systems (Brown, 2000). The modelling challenge is to bring both the biological and the economical parts together without loosing the essence of either. Hammond and Dubé (2012) see system dynamics (SD) as an approach of particular interest for such analysis. This is because it is able to capture the dynamic complexity of food systems in a multidimensional way.
SD has already been used as an approach to analyse food and agriculture related questions in numerous studies (to give three examples: Bach and Saeed, 1992, Nicholson and Stephenson, 2014, Stephens et al., 2012). Implicitly all these studies apply quantitative assumptions and mathematical relations for modelling food systems and agricultural processes. However, so far there is no explicit translation of agronomic and agricultural economic theory into SD.
For theory building, this paper explicitly links standard agronomic and agricultural economic theory to the SD approach and thus creates an integrated, dynamic bio-economic model. It does so by using Zambia's maize production system as a study case.

The case of Zambia is interesting to study for several reasons: first because continued, chronic food and nutrition security problems are major outcomes of its food system (Tembo and Sitko, 2013). Total per capita calories availability was estimated to decrease from around 2200 kcal per person per day in 1984 to around 1900 in 2011 (Figure 1a). A main driver behind this outcome is the population that was increasing over the past three decades and is projected to continue increasing during the coming decades (Figure 1b).

Figure 1: a) Kcal availability per capita per day in Zambia from 1984 to 2011; b) Population estimate and projection in Zambia from 1984 to 2050.



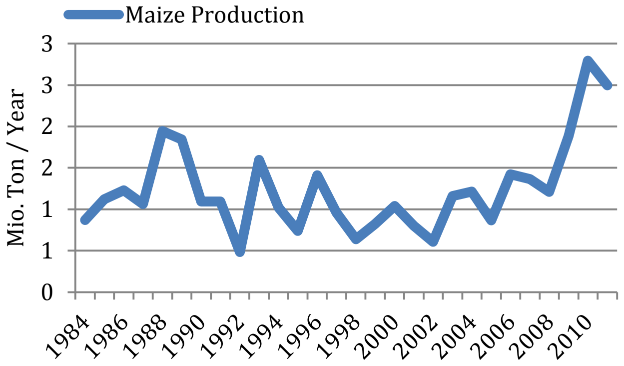
a) Source: FAO (Various-b)

b) Source: FAO (Various-c)

The second reason for choosing Zambia for this study is the extreme focus of the agricultural sector on maize. Introduced during the colonial time, the plant plays a dominant cultural role as Zambia's staple crop, which has also endured after independence in 1964 (Kajoba, 2014). It is especially important in the small holder farming sector where up to 90% of the producers grow maize (Tembo and Sitko, 2013). Over the period from 1984 to 2011 maize accounted on average for 56% of the total calorie intake with a decreasing trend starting at 60% and being around 50% in 2011 (FAO, Various-b)(Figure 1a).

Thirdly, Zambia is interesting because of the dominant role of its low endowed agricultural sector: With trade being unpredictable and politically driven, the country's food security depends heavily on the domestic maize production that is volatile due to unstable rainfall and input availability (Chapoto and Jayne, 2009, Kajoba, 2014, Burke et al., 2010)(Figure 2). While land for food and in particular maize production seems to be abundant in Zambia (Tembo and Sitko, 2013), soil fertility is low and seems to have decreased over the last decades (IFDC, 2013). Agriculture is the most important employer of the country and is at the basis of two thirds of all livelihoods (Tembo and Sitko, 2013). Rural poverty rates remain high at around 80%, indicating low endowment of Zambia's smallholder farm sector (Chapoto et al., 2011).

Figure 2: Maize Production in Zambia from 1984 to 2011.

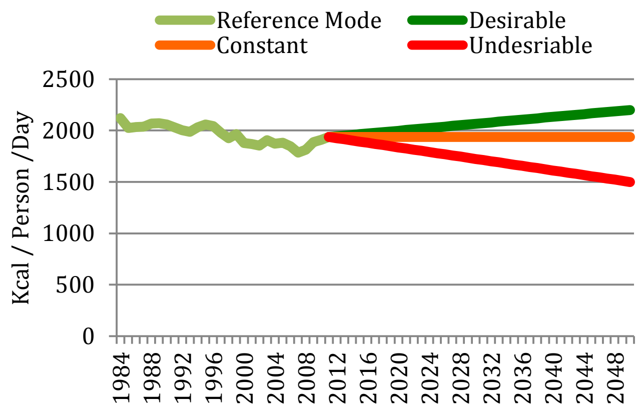


Source: FAO (Various-d)

Fourth, with its enduring role as staple crop, maize is not only economically important but also politically (Mason, 2011). In order to stabilise the maize sector and its prices, the government of the Republic of Zambia (GRZ) intervenes in two main areas: it provides subsidised inputs to farmers (predominantly fertilizer) and it also intervenes into the maize market through parastatal marketing organisations (former NAMBOARD[1], today FRA[2]). The marketing interventions through NAMBORD/FRA consist of setting a national producer price at which strategic maize reserves are bought and then sold at subsidised conditions to millers. These two areas of political intervention traditionally account for a large share of GRZ agricultural expenditure (Wood et al., 1990, Mason, 2011). The expenditures were scaled back during the period of political liberalisation in the 1990ies (e.g. Seshamani, 1998). So far the policies are critiqued for their lack of a clear pro-poor focus (FSRP, 2009, Mason and Myers, 2013) and were not able to fully ensure food security (Figure 1a).

While the characteristics of Zambia's food system are interesting to study from a scientific point of view, the challenge they put on the country's agricultural sector and the natural resources are huge: how can per capita food availability be enhanced – or at least be kept at the current level – facing the demand of a rapidly growing population? (Figure 3) In this paper I develop and calibrate a bio-economic model for the maize sys-

Figure 3: Reference Mode with different Development Paths



[1] National Agricultural Marketing Board

[2] Food Reserve Agency

tem in Zambia. Based on this model different policies to enhance food availability are tested and evaluated. The main contribution of this paper is twofold:

- First it contributes to the existing SD literature as a theory building paper. The model construction is done by taking relevant agronomic and agricultural economic theories from standard textbooks, and translating, specifying and linking them piece-by-piece into an SD framework. Although numerous SD models in the field of agriculture are published already, such an explicit link between relevant theories and the SD approach is new.
- Second the paper contributes to Zambia's nutrition challenge by studying food availability from a systemic, endogenous point of view. While different works analyse individual parts of the food system (e.g. works from the Indaba Agricultural Policy Research Institute), this study offers an integrated bio-economic simulation tool to investigate food availability and in particular the maize system.

The next section translates relevant agronomic and agricultural economic theory into a causal system approach and is specified in the subsequent part. After a part describing data sources, calibration and validity the base scenario is introduced. In the base run and sensitivity testing sections the base run and some sensitivity analysis are presented. In the policy testing part the two current maize policies are projected into the future and their potential is compared to two alternative policies focusing on natural resources. The paper concludes by drawing policy recommendations.

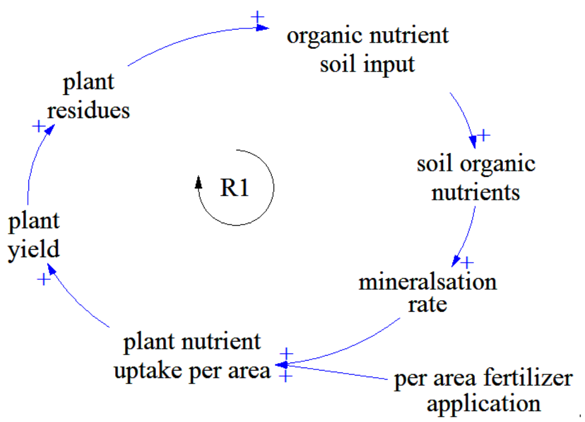
Theory

I build the model for a time horizon of decades on an aggregated sector level based on the general food system framework of Ericksen (2008) that was adopted and specified from a feedback perspective in Gerber (2014). The commodity models from Meadows (1970) and (Sterman, 2000) serve as SD backbone. Whenever possible I discuss and use relevant theories from a broad perspective in order to allow for generalisation. In some cases, however, the focus on the case study was unavoidable. The section below presents theories and their integration in this study.

Yield and Soil Nutrient Dynamics

A central construct in agronomy is the yield. It can be defined as the quantity of plant parts per area and time unit, produced for a main, specific purpose (Schilling, 2000; p.12). There is a long tradition in agronomy to assume that yields are a product of the allocation of different production factors (such as nutrients, water etc.) and therefore to establish input-output relationships, especially in plant production. Since Turgot (1766) various production functions have been formulated, discussed and applied to represent yields (Fandel, 2000; p.26). Heady and Dillon (1961) give an overview of mathematical relationships that might be used for different crops, locations and purposes; and research in the field is still going on (e.g. Amon-Armah et al., 2014, Llewelyn and

Figure 4: Reinforcing Nutrient Plant Yield loop.

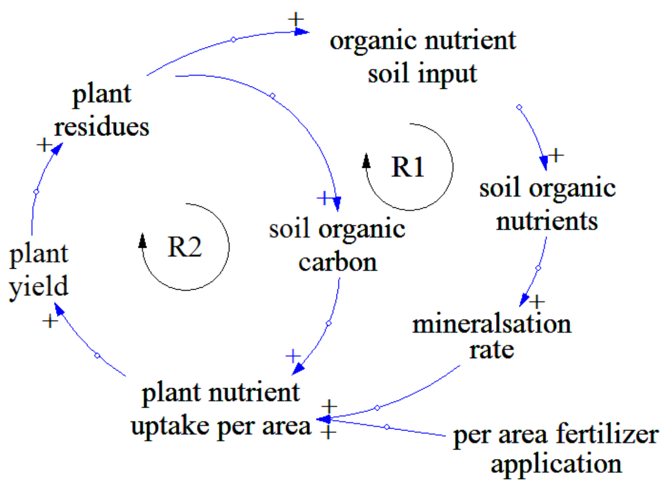


Featherstone, 1997). A common feature however is, that they assume an increasing output with increasing inputs – up to a certain point after which yields are decreasing with higher values of production factors.
The yield relations for nutrients are captured in the lower part of Figure 4, which shows mineralisation rate and fertilizer application positively influencing plant yield through the intermediate variable plant nutrient uptake. For the low endowment agriculture in Zambia solely a positive relation is assumed and since the model uses aggregated national average values the likelihood that negative returns on increasing production factors occur is very small over the coming decades.

As a side effect of this main production, subsequent plant biomass is produced that is not used for the main purpose and partly remains on the field as plant residues containing nutrients (Scheffer and Schachtschabel, 2010). The nutrients are worked into the soil as part of soil organic matter (SOM).
This positive link is capture in Figure 4 from plant yield to soil organic nutrients with the intermediate variables plant residues and organic soil nutrient inputs. From an SD point of view it is worthwhile mentioning that the link from plant yield to plant residues is correlational and that especially plant growth models with smaller time units and less aggregated levels first calculate total biomass production and then disaggregate it into yield and plant residues. However, on an aggregate level the above proposed approximation finds support (e.g. IPCC, 2006).

Scheffer and Schachtschabel (2010; p.73) suggest that the mineralisation of SOM is positively related to the soil organic matter and varies according to a number of factors such as soil moisture, temperature, clay content, soil pH and nitrogen availability. Therefore I assume that also the link between soil organic nutrients and nutrient mineralisation rate is positive creating the first reinforcing nutrient plant yield loop (R1). Although reinforcing in nature, this loop has to follow the law of mass balance and depends on external addition or removal of nutrients (e.g. through fertilizer application or yield removal).

Figure 5: Reinforcing Soil Organic Matter Yield loop.



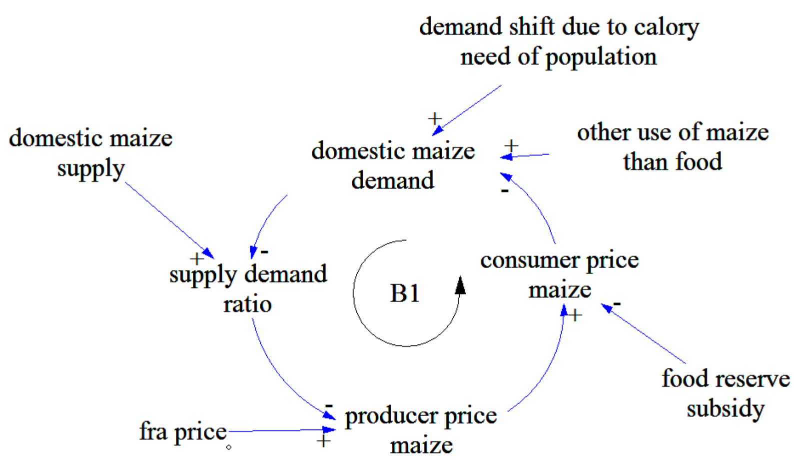
While the R1-loop process focuses on soil organic nutrients, SOM itself is an important soil component influencing physical, chemical and biological properties of soils (Shitumbanuma and Chikuta, 2013; p.45). One of these properties is the potential to exchange and store ions such as nutrient molecules (Scheffer and Schachtschabel, 2010; p.68). This can prevent nutrients from being lost due to leaching, runoff and gasification and increases the plant nutrient uptake.
This mechanism is added to the R1-loop in Figure 5 by positively linking plant residues with plant nutrient uptake through the intermediate variable soil organic carbon (representing SOM). While the R1 loop represents soil fertility directly through the soil organic nutrients, the new R2 loop represents soil fertility in a broader sense. It captures the building up or degrading of SOM represented by its backbone soil organic carbon. In the case of Zambia soil fertility is low and even seems to decline (IFDC, 2013; p.30) and yield response to fertilizer is

rather low among others due to low levels of soil organic matter (Tembo and Sitko, 2013; p.22). It means that in practice this is a "dormant" loop, which - once "activated" - helps to increase plant nutrient uptake and therefore the efficiency of applied organic and mineral fertilizer.

Supply, Demand and Prices

Agricultural markets and price building are typical areas of agricultural economics. Microeconomic theory in general (e.g. Varian, 2007) and agricultural economics in particular (Henrichsmeyer and Witzke, 1991) assume that market mechanisms equilibrate supply and demand quantities through price setting. For goods with commodity character the theories suggest that an increase of the supplied quantity - ceteris paribus - has a decreasing effect on the market price. Since microeconomic theory usually takes a static view the conceptualisation of this mechanism was built on Sterman (2000).

Figure 6: Balancing Supply/Demand Price Loop including Government Food Reserve Policies.



The relations from supply and demand to the producer price are captured in Figure 6 through the intermediate supply demand ratio variable. The link from supply to the producer price is assumed to be negative and the link from demand to producer price is assumed to be two times negative resulting in a positive link if summarised. Note that unlike in microeconomic theory the model does not assume equilibrium. However, there is still no inventory stock as suggested by Meadows (1970) and Sterman (2000). The reasons are that the available (implicit) maize stock data for the study case is inconsistent[1] (FAO, Various-b) and maize is difficult to store for long periods on small holder farms. I therefore assume that each year the supplied quantity is consumed before the next harvest, probably being a realistic assumption with the population projection in Figure 1. Another case specific addition is the link from the FRA price to producer price, acting to stabilise maize price with a lower limit.

The link from producer price to consumer price summarises the maize supply chain and is assumed to be positive. The difference between the two prices consists of the aggregated handling costs, the margins of the value chain's actors and the reserve subsidies.

According to Henrichsmeyer and Witzke (1991; p.295) the demand of food is dependent on different factors such as the product price, prices of substitutes, income and needs. From these factors the product price is seen to be the most important. And in addition, especially from an aggregated perspective, Henrichsmeyer and Witzke (1991; p.302) see population as a main driving force of food demand. They stress that population growth

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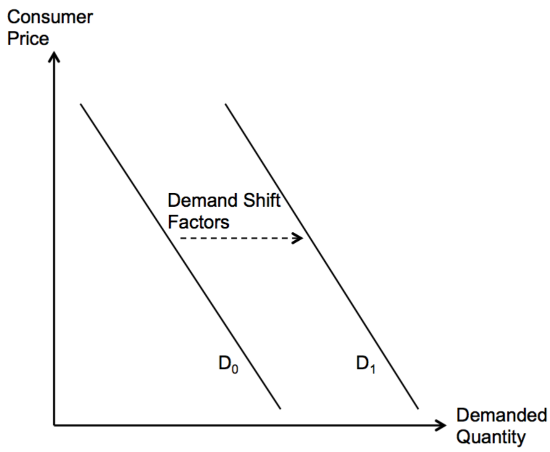
[1] When year-by-year inventory data is added up to a dynamic series, the calculated inventory stock would once reach five times the amount of an average yearly production while people suffer from hunger simultaneously.

in low-income countries often doesn't leave any room to increase per capita food availability.

The link from consumer price to domestic demand maize is assumed to be negative as incorporated in Figure 6. This link closes the balancing supply/demand loop (B1) adjusting the demand to the given price. In addition to the price link I assume demand to be a function of demand shift factors such as population and non-food sectors as conceptualised in Figure 7.

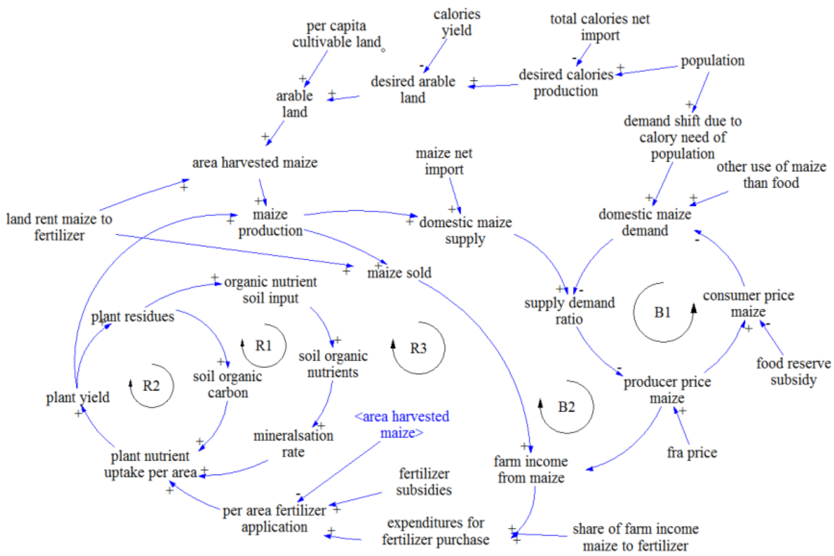
Figure 7: Demand Curve Conception.



Allocation Decisions

To connect the loops above and embed them into a broader food system framework, farm decisions need to be added (Figure 8). Microeconomic theory generally assumes that inputs are allocated at the level generating the highest profit (e.g. Varian, 2007). Agricultural economists such as Henrichsmeyer and Witzke (1991) agree that optimising profit is a target of farmers, however that other goals and uncertainty might influence farmer's (input) allocation decisions, as well. To formulate a rational, profit maximising input allocation mechanism becomes complex with an increasing number of inputs and their possibilities of combinations.
For practicality I restrict the endogenously included decisions to two inputs: land and fertilizer. The inputs are chosen according to their importance in Zambia (Burke et al., 2010) and the allocation decisions are assumed to be based on local instead of general theoretical foundations.

Figure 8: Model overview including the reinforcing production income loop (R3) and the balancing price income loop (B2).



Allocation of Arable Land

Theoretically, land allocation is determined by different factors (e.g. Lambin et al., 2001). In developing countries population – through calories need – is an important factor determining the level of arable land (Pinstrup-Andersen and Watson, 2011). In the case of Zambia arable land is potentially abundant. In practice, however, actual land use is restricted due to limited access (because of geographically concentrated settlements) and low endowment of households and the agricultural sector in general (Hichaambwa and Jayne, 2012).

The theoretical link from population to desired arable land is conceptualised through desired domestic calories production and assumed to be positive (corrected for net caloric imports and domestic yields). If more/less calories are imported less/more calories are needed from domestic sources. And if domestic yields are high, less land is needed in order to produce the desired calories than if yields were low. Arable land is assumed to be restricted by a maximal per capita cultivable land reflecting the limited access and low endowment.

Allocation of Maize Area

In the case of Zambia many smallholder maize producers are subsistence farmers and their main goal is assumed to be food security and profit is of secondary interest (Chapoto et al., 2012). For determining the maize area from total arable land, allocation rules solely based on profit seeking are therefore not appropriate. In his commodity model Sterman (2000) uses a profitability indicator to model the effect of capacity adjustment. Such an effect formulation leaves room to account for other goals.

Based on Stephens et al. (2012) I therefore use "average value product" or "land rent" (per hectare revenue minus per hectare fertilizer expenditures) as a profitability indicator of the area under maize cultivation. However, this profitability indicator must be corrected for the food security goal of the Zambian farmers in the equation specification. The link from land rent to the area under maize production is assumed to be positive.

Allocation of Fertilizer

In Zambia fertilizer is partly provided under subsidised conditions (e.g. Wood et al., 1990, Mason and Myers, 2013); however, the physical availability is often too little to reach the economically demanded quantity. The use is therefore strongly determined by other (political) means(e.g. IFDC, 2013). In this case it is inadequate to apply economic theory. I therefore use an exogenously calculated "share of maize income" to determine the fertilizer expenditure.

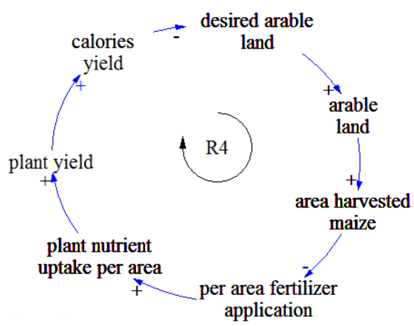
Sales Decision

Since only parts of the total maize harvest are sold a mechanism determining the share sold is introduced. To comply with the food security goal, as well as with economic motivation of farmers the following two links are assumed to determine the share sold: a positive link from per capita food availability to the share sold indicating that the more food is available the more subsistence oriented farmers are willing to sell some of their production. And another positive link is assumed form land rent to the share sold indicating that the more profitable it is to sell maize, the more is actually sold.

Additional Loops

The decision structures described above add numerous loops to the model. This is especially true since land rent is endogenised. It is therefore not possible to describe all the added loops. Instead the three most important loops are selected: the reinforcing production income loop (R3, Figure 8) can either augment or drain farm income; therefore yields and production depend on its direction. This mechanism on the other hand can be counteracted by the balancing price income loop (B2, Figure 8). While more production ceteris paribus leads to higher sales of maize, it also leads to lower producer prices and therefore to a lower farm income. The relative strength of the two loops is an empirical question, however, in the case of a growing

Figure 9: Reinforcing Land Yield loop.



demand it can be expected that the R3-loop might be stronger.

Another important but so far dormant loop is displayed in Figure 9: the reinforcing land-yield loop (R4). It acts in the following way: the more area under production the lower per area fertilizer applications and therefore yields (under a given quantity of fertilizer). And the lower the yields are, the more land is needed to realise the desired production.

Model Specification and Key Equations

The theoretically founded links need to be specified in order to formalise the model. The following section gives an overview of a few key equations in the model. A more comprehensive overview of model equations is presented in the annex.

Production

The production of maize is represented in the model by a multiplication of the average maize yield and the area on which maize is harvested:

$$Maize\ Production = Yield\ Maize \times Area\ Harvested\ Maize$$

Yield Formulation

The many alternatives of production functions don't make it an easy task to choose an appropriate equation for yield. My criteria for selection were:

1. Applicability on a large geographical and temporal scale
2. Therefore also allowance for factor substitution
3. Empirical support
4. Adequacy of complexity compared with the rest of the model.

I choose a Mitscherlich-Baule formulation including the factors water and nitrogen because they seem to be most relevant in the case of Zambia (Burke et al., 2010, Shitumbanuma and Chikuta, 2013). While in theory a stage III production function would be most adequate (Henrichsmeyer and Witzke, 1991) the Mitscherlich-Baule formulation is a stage II representation. However, its application for average yields on a large scale and the low level of factor availability (IFDC, 2013) should justify this limitation. Alternatively square root functions were tested providing acceptable fit with empirical data. However, they were left aside because they were conflicting with criteria 2 and 4. A linear min-function was also considered; however, left aside because it is conflicting with criteria 1, 2 and 3 (Kuhlmann, 2010). And although a detailed plant growth model would have been an alternative from a causal perspective, it was not considered since it conflicts with criteria 1 and 4.

The applied Mitscherlich-Baule formulation is of the following form (Schilling, 2000):

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

With y representing the average maize yield, A is the yield plateau representing a potential yield under perfect factor availability, c_1 and c_2 are constants and x1 and x2 are the factor uptakes (water and nitrogen, taking into consideration nitrogen from soil and mineral fertiliser). A is assumed to be 9 tons per hectare and year, representing a mix between local and high yield hybrid seed. The constants c_1 and c_2 are model specific parameters, in this case: c_{water} = 0.0053 and $c_{nitrogen}$= 4.5.

The development of the organic soil element stocks carbon and nitrogen are represented in the following way:

$$\frac{dE}{dt} = Ie,p + Ie,a - \frac{E}{tmin}$$

Where E is the amount of organic element per hectare. The first two terms of the equation ($I_{e,a}$ and $I_{e,p}$) are per hectare inputs of organic element from two sources (a: animals, p: plant residues) where the animal input is taken from data (FAO, Various-a) and the plant residue input is calculated according to IPCC (2006). The last term of the equation represents the mineralisation rate of each element and is taken from Scheffer and Schachtschabel (2010; p.73). Since both, carbon and nitrogen, are part of the SOM the parameter t_{min} is assumed to be equal for the two elements. It was endogenously calibrated to obtain an acceptable data fit and is assumed to be 37.4 years, being in the range of Scheffer and Schachtschabel (2010; p.73).

And the link from soil organic carbon (representing SOM) to nutrient plant uptake is established theoretically: Oberholzer et al. (2014) even explicitly state that there "*is positive feedback between crop yields and SOM*". However, the link between SOM and yield has not yet been clearly established mathematically (Pan et al., 2009). I therefore assume the following relationship:

$$N\ uptake = N\ mineralised * reference\ N\ uptake\ share * \left(\frac{SOC}{Initial\ SOC}\right)^{Uptake\mathcal{E}}$$

Where SOC is soil organic carbon, and Uptake$\mathcal{E}$ is the elasticity of SOC on plant uptake.

Allocation of Arable Land

The allocation of arable (represented in the model by total area harvested) is split into three processes. A first one determines the desired arable land through the number of calories needed by the population. This is assumed to be a function of the number of people, the average daily energy requirement (ADER, which is assumed to be a constant with the value of 2200 kcal per person per day) and the share of calories originating from plants (estimated from FAO (Various-b) and assumed to be constant at 94%). The total caloric need is reduced by the amount of caloric net import, implemented exogenously due to heavy political interference into the trade regime (Dorosh et al., 2009). The resulting domestic caloric need is divided by the average caloric yield in order to receive the desired arable land area:

$$Desired\ Areble\ Land = \frac{Calories\ Need\ Population - Calories\ Net\ Imports}{Average\ Yield\ in\ Calories}$$

A second process determines the realistic arable land demand by comparing the desired arable land with the maximum arable land. The maximum arable land is determined by land accessibility by the population and the endowment of the agricultural sector such as capital, assuming that one agricultural workforce can on average cultivate at maximum 0.55 hectares per year. This constant would increase with an increase in land accessibility or per capita capital endowment.

$$Realistic\ Arable\ Land\ Demand = \min(Desired\ Arable\ Land, Maximum\ Arable\ Land)$$

And the third process determines the change of the arable land stock (AL):

$$\frac{d\ AL}{dt} = \min\left(\frac{RALD - AL}{AL\ AT} + \text{ALOL}, \frac{NUP\ AL}{AL\ AT}\right) - \text{ALOL}; \quad \text{with ALOL} = \frac{Des\ OL - OL}{OL\ AT}$$

where the first term of the right equation side determines the addition of land from potential arable land that is not in use yet (NUP AL); this is assumed to be all the forest, pastures and meadows. It either takes the difference of the realistic arable land demand

(RALD) and AL divided by the arable land adjustment time (AL AT is assumed to be 4 years) adjusted for the outflow to other land (ALOL) in order to avoid steady state errors or the total NUP AL divided by the AL AT if UNP AL availability is limiting. The later is however not assumed to happen since land can be assumed as an abundant resource in Zambia (e.g. Tembo and Sitko, 2013).

The second term of the right equation side determines the outflow (ALOL) of arable to other land (OL), which is mainly settlement land. Its desired level (Des OL) is determined by the population and the per capita need (assumed to be 0.1 hectare per capita). The other land adjustment time (OL AT) is assumed to be 2 years.

Allocation of Maize Area

The profitability indicator of maize area is calculated the following way:

$$Land\ Rent = Revenue - Expenses = (Y \times PP) - (\frac{Ctot}{AHM})$$

Where y is the maize yield, PP the producer price for maize, C_{tot} the total maize sector costs and AHM the area harvested maize. Dynamic data for C_{tot} is not available. Therefore C_{tot} is approximated by total farm fertilizer expenses, the largest individual cost category (Burke et al., 2011). Through a linear relationship the share of maize area on total arable land is estimated, providing the best empirical fit (R^2=0.49). Intercept and slope were recalibrated endogenously since 8 of 26 values for land rent were missing for exogenous calibration:

$$Share\ of\ Maize\ on\ Total\ Area = 0.31 \times \frac{Land\ Rent}{Initial\ Land\ Rent} + 0.28$$

The formulation implies that even if average economic incentives to produce maize are low (e.g. land rent < 0) the share of maize area can be higher than zero. This is in line with the dietary importance of maize and some subsistence farmer's priority of food security[1], as well as with the fact, that some framers still may make profit even if average profits are below zero.

Supply, Demand and Prices

Demand for maize is modelled according to Sterman (2000; p.811-813) and with the following addition for demand curve shift:

$$Shift = Population \times ADER \times Share\ of\ maize\ on\ Diet - Refrence\ Demand$$

With ADER = 2200 kcal/person/day and "Share of maize on total diet" taken from data.

The quantitative reaction of maize demand to a change in consumer price is assumed to be inelastic with an elasticity of reference industry demand of -0.1. This reflects the culturally important role of maize as a staple crop.

Since the producer price depends on the demand coverage, as well as the FRA intervention it is assumed that the FRA price acts as a floor price, however, if private actors pay more this higher price is realised (Mason, 2011):

$$Producer\ Price = \max(FRA\ Price, Price\ Indicated\ from\ Supply\ Demand\ Ratio)$$

[1] Oral message from Dr. Progress Nyanga, The University of Zambia

Data, Calibration and Validity

Different data series were used to calibrate the model (Table 1). Since data collection in Zambian agriculture was improved after independence (Wood et al., 1990; p.189) the historical period starts in 1984 when core data series such as yield and area seem to be robust. The model was calibrated using the period from 1984 to 2011.
Barlas (1996) differentiates between two main categories of tests for model validation: structure and behaviour oriented tests. For practical application, however, it is argued in Barlas et al. (2000; p.53) that

> *"The qualitative and long nature of these tests makes it impossible to show the results in the context of such an article. We simply state that the model was found to be structurally reliable and show some results that demonstrate its behavior validity."*

This statement is valid for this article, as well. I want to stress, however, that the direct structure tests received a special focus as can be seen in the theory and specification parts above. And in behaviour oriented validity tests the emphasis was on long-term trends and only to a lesser extent on year-to-year variations.

Table 1: Data Series, Usage and Source.

Data Series	Usage	Source
Total Population	Model Input, Scenario	FAO (Various-c)
Total economically active population in Agriculture	Model Input, Scenario	FAO (Various-c)
Yield Maize	Calibration	FAO (Various-d)
Area Harvested Maize	Calibration	FAO (Various-d)
Production Maize	Calibration	FAO (Various-d)
Total Area Harvested	Calibration	FAO (Various-d)
Maize Trade	Model Input	FAO (Various-b)
Maize for Non-Food Use	Model Input	FAO (Various-b)
Land Use	Input and Calibration	FAO (Various-e)
Land Rent	Calibration	Calculated
Producer Price	Calibration	Kumar (1988); Wood et al. (1990); Mason and Myers (2013)
Consumer Price	Calibration	Kumar (1988); MAOC (Various)
Food Reserve Subsidies	Model Input	Wood et al. (1990); Howard et al. (1993); Zulu et al. (2000); Chiwele et al. (2010); GRZ (Various)
Fertilizer Use	Calibration	FAO (Various-e)
Fertilizer Prices	Calibration	Estimated from MAOC (Various)
Fertilizer Subsidies	Model Input	Wood et al. (1990); Howard et al. (1993); Zulu et al. (2000); Chiwele et al. (2010); GRZ (Various)
Rainfall	Model Input	ZMD (Various)
Animal Input to plant production	Model Input, Scenario	FAO (Various-a)
Soil Organic Carbon	(Calibration)	No dynamic data available! Qualitatively: IFDC (2013)
Soil Organic Nitrogen	(Calibration)	No dynamic data available! Qualitatively: IFDC (2013)
Non-Maize Food Supply	Model Input	Calculated from FAO (Various-b)
Non-Maize Yield	Model Input	Calculated from FAO (Various-b)
Energy Share of Maize on Total Diet	Model Input	Calculated from FAO (Various-b)
Sales Maize	Calibration	Wood et al. (1990); CSO (Various)

Base Scenario

To run the model into the future different assumptions for exogenous inputs need to be specified. For the base scenario the social environment is assumed to be characterised by an exponentially growing population and a per capita economic performance similar to the average over the historical reference period.

In practice, the following assumptions were made for the base run: population projections according to FAO (Figure 1), no FRA price since it is politically and not economically determined, food reserve and fertilizer subsidies are estimated to be constant at the average level over the reference period. Trade is assumed to be zero since it is unpredictable and depends on political decisions instead of economic rational. Fertilizer prices, the share of farm income to fertilizer, average value added and rainfall are assumed to be constant on the average level of the reference period. And the yield of non-maize is assumed to increase from 2012 to 2050 by 1 Mio. Kcal per ha per year (+16%) due to productivity increases and changes in the crop mix.
Data values for a few variables were available longer than for the calibration period. Assumptions for the future therefore begin after the latest data points and policies start in 2014.

Base Run

Figure 10 provides an overview of key variables comparing the base run to data points during the reference period from 1984 to 2011, as well as of simulations until 2050 under the assumptions for the base scenario. The discrepancy between simulation and data for "food supply maize" and "food supply total" can be explained by unrealistic inventory values in the data, making the supply data series too smooth.

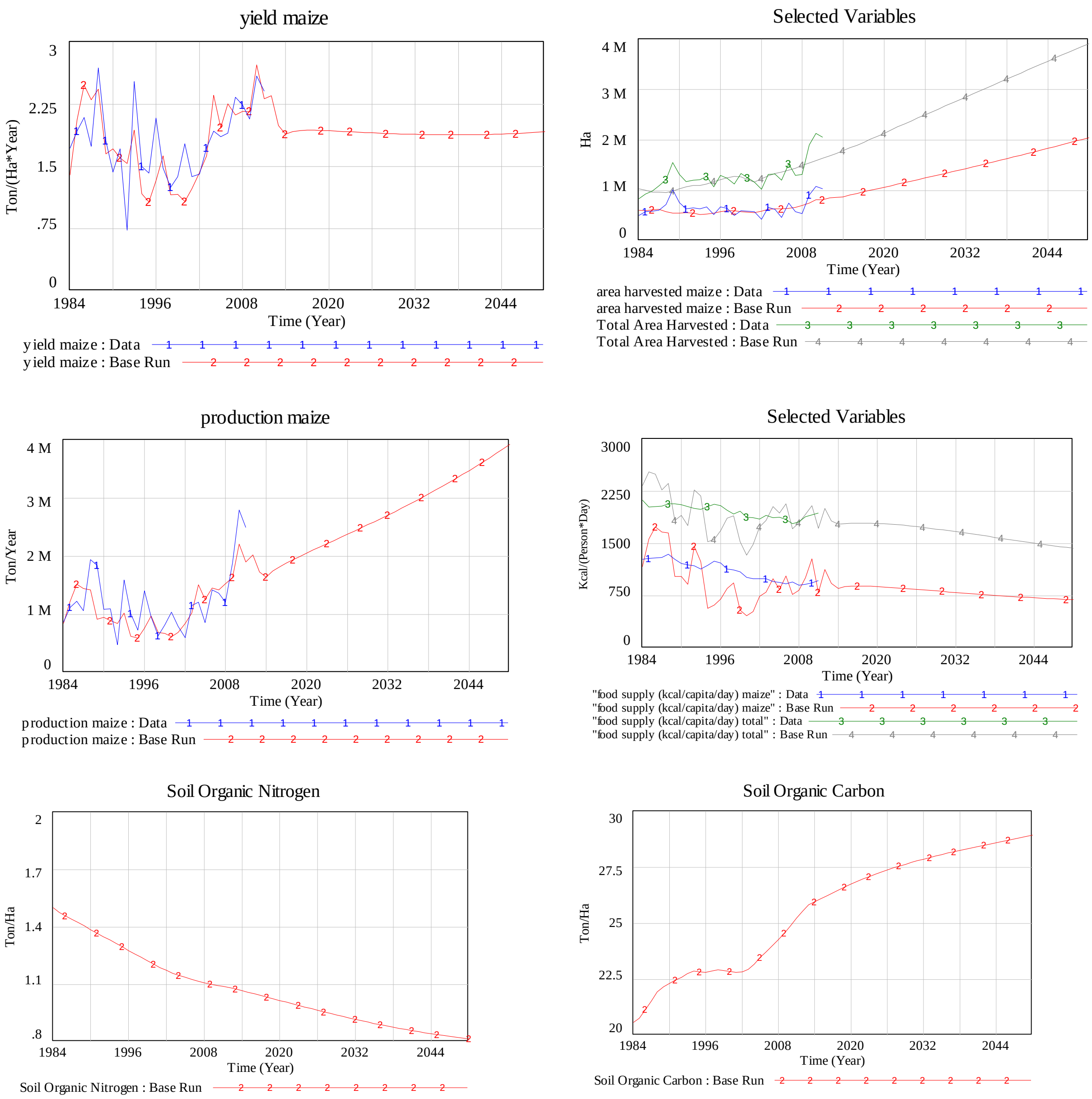
In the base run both soil fertility stocks (soil organic carbon and soil organic nitrogen) are at low levels (according to Scheffer and Schachtschabel, 2010). Due to a lack of dynamic, empirical data a comparison to a historical reference mode is not possible (IFDC, 2013). However, qualitatively the simulation results are in line with empirical observations stating that soil fertility is low in Zambia (e.g. Shitumbanuma and Chikuta, 2013).

Given the low level of soil fertility, maize yields are dependent on fertilizer application and therefore to a large extent on the fertilizer subsidies. These were low during the 1990ies, a period of political liberalisation (Jayne et al., 2003), explaining the low yield during the period. Since land use for maize production was stagnant through large parts of the reference period, maize production followed the yield trend. It could, however, not cope with the increasing demand from population resulting in decreasing per capita kcal availability. Only through the last decade or so an upward trend in land allocation can be observed.

For the future period the growing population increases the demand for both, food and land. Arable land and the maize area are increasing to the maximum allowed by the current land access and capital endowment, driving production up. While the farm income loops (R3 and B2) both work to increase the farm income (resulting in higher absolute fertilizer application), the R4 loop - driven by the increase of land - decreases per ha fertilizer availability. And since both soil fertility loops (R1 and R2) run with low stock levels, the maize yields even decrease before they stagnate at a low level of around 1.9 tons per ha compared to the yield potential of 9 tons per ha yield.

As a consequence the kcal availability drops down from around 1800 in 2014 to 1430 kcal per person per day in 2050 indicating severe famines. With such a low food availability (compared to the desired 2200 kcal per person per day) the exogenous population growth might be an unrealistic assumption. In order to improve food system outcomes alternatives to the base run need to be found.

Figure 10: Simulation results and data (if available) for key variables during the reference period from 1984 to 2011 and the base run up until 2050.

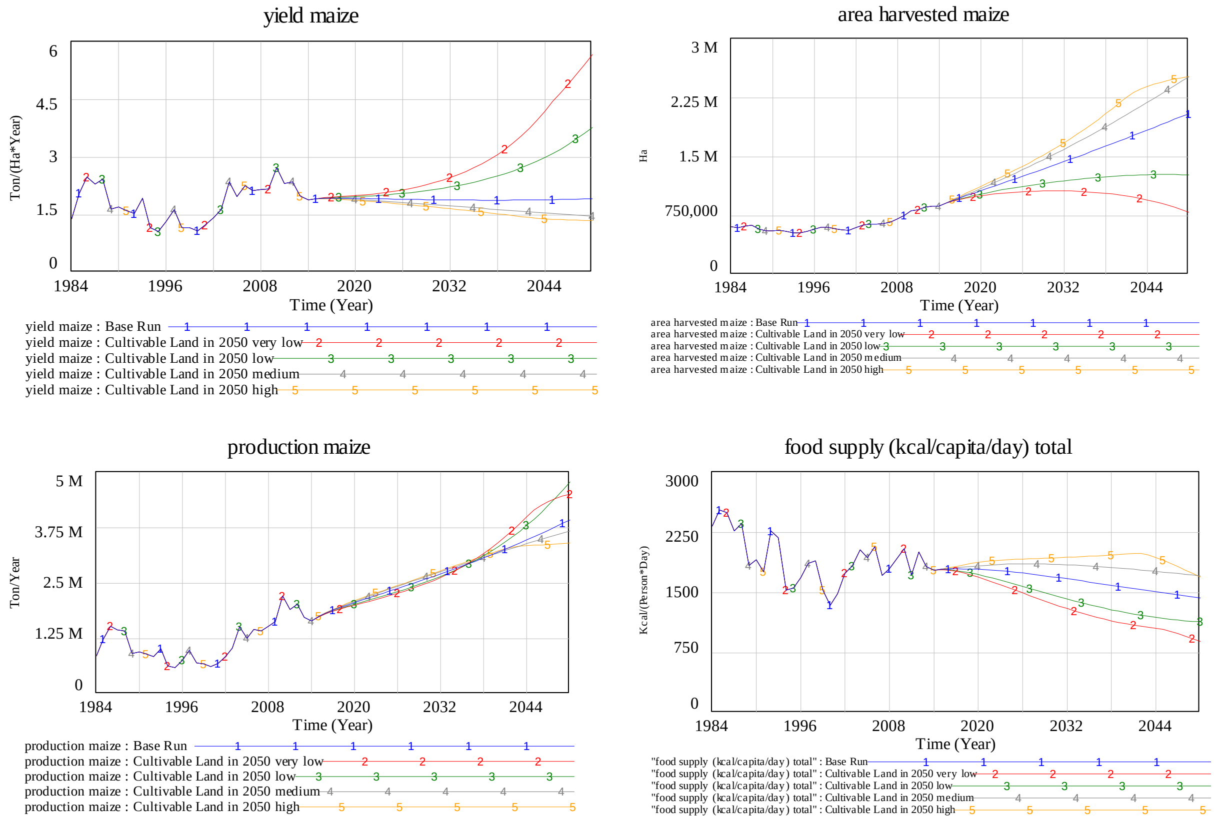


Sensitivity Testing

Before looking into alternatives to the base run, sensitivity test were conducted: first to test the model validity and second to identify interesting areas for policy formulation. During this process two areas of special interest were identified and are presented below:

The first area concerns arable land that is not used up to its potential. Land cultivation is limited by access and low endowment. To test the sensitivity of the model in this area the parameter representing the per capita cultivable land (number of hectares that can be cultivated per person per year) is varied. Parameter changes are described and results displayed in Figure 11.

Figure 11: Sensitivity tests with different values of per capita cultivable land. All runs start with 0.55 ha/person/year in 2014 and change linearly until 2050 (in the case of "very low" to 0.1, in "low" to 0.25, in "base run" constant at 0.55, in "medium" to 0.75 and in "high" to 1).



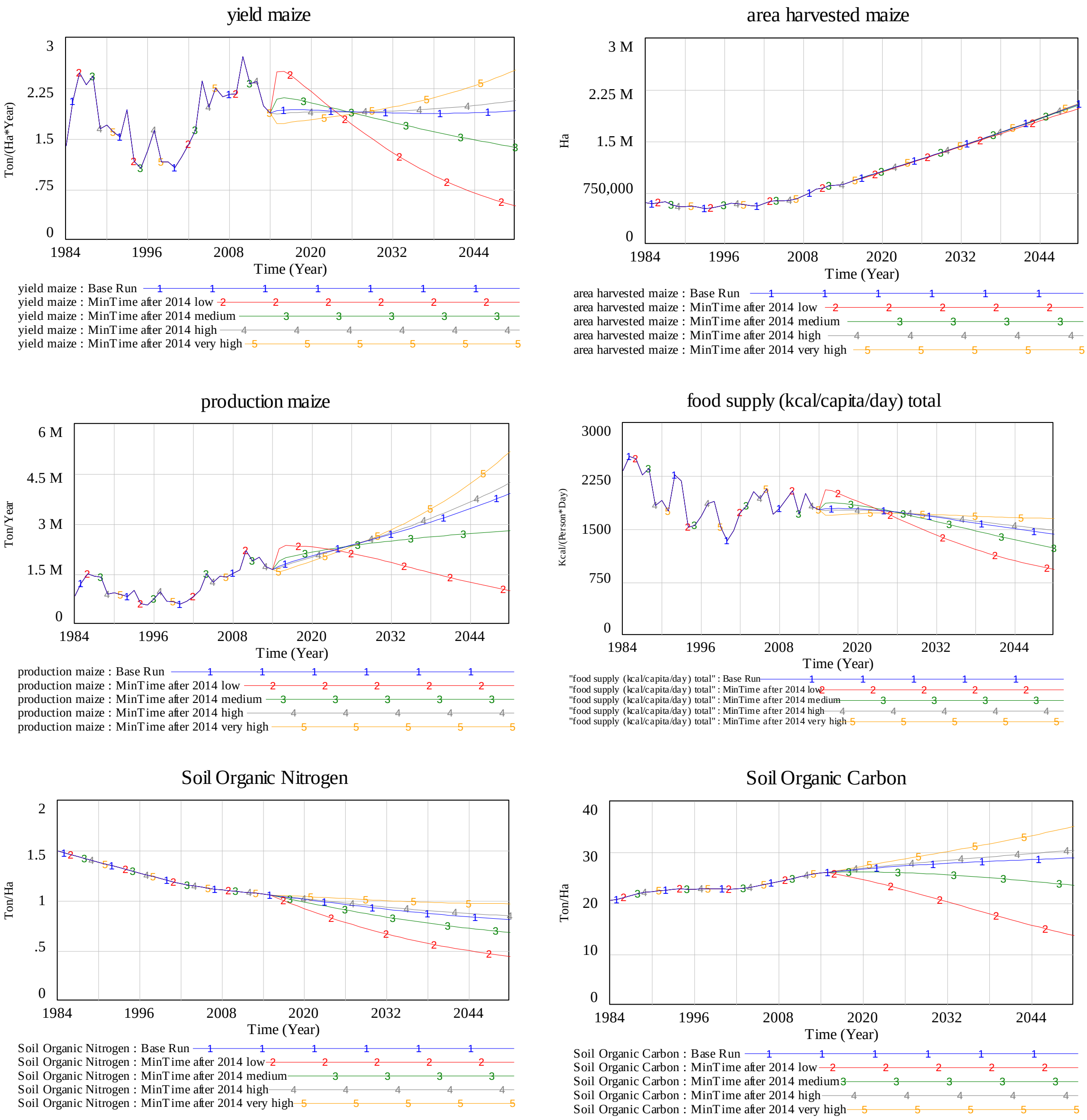
Simulation results suggest that the use of arable land and land for maize production reacts in a sensitive way if the per capita cultivable land is varied. If the parameter is increased/decreased, also the allocated land (both, arable and maize) increases/ decreases. This happens because the per capita cultivable land currently restricts land use to reach the desired arable land level. However, such a variation of land also has consequences in other parts of the model: it causes the maize yield to change in the opposite direction through the R4-loop (due to a change in per hectare fertilizer availability). These two mechanisms balance each other out resulting in a similar maize production for all parameter values. This observation is in line with findings from Mason et al. (2012).

While maize supply is similar for all parameter values, total per capita food supply changes with the parameter variation. This happens first because the area allocated to other plants than maize varies with the parameter variation and second because of the assumption of equal non-maize-yields for all parameter values, which is realistic for important non-maize plants such as cassava due to their input independence (Chitundu et al., 2006). The decreasing growth in the "high capital" run of area maize during the 2040ies occurs because of a model mechanism balancing the production factors capital and fertilizer under extreme conditions (area growth is restricted if per hectare fertilizer availability is low).

The sensitivity tests above indicate that the model reacts adequately to a change of labour productivity: the importance of maize lets the production increase with the population's demand. And the variation of total food availability is mainly coming from a variation of the area of other, culturally less dominant crops such as cassava, millet, sorghum, rice, etc.

The second area of special interest is the soil fertility mechanisms (R1- and R2-loops). To analyse the model behaviour with changes in the soil fertility area, the SOM mineralisation time is varied as described and presented in Figure 12.

Figure 12: Sensitivity tests with different values of SOM mineralisation time. All runs have the value of 37.4 years up to 2014 and then change to another constant value up to 2050 ("low" to 20, "medium" to 30, "base run" constant at 37.4, "high" to 40 and "very high" to 50).



Simulation results show that model areas react differently to a variation in SOM mineralisation time: a small mineralisation time leads to a depletion of the SOM stocks through a higher mineralisation rate. The higher mineralisation rate of nitrogen lets maize yields increase in the beginning (after 2014). However, due to the stock depletion, maize yields start to decrease soon and continue to do so in the long run, falling below the value of higher mineralisation time runs (R1- and R2-loops). Exactly the opposite behaviour is observed if the SOM mineralisation time has higher values. Maize yields first drop due to a lower mineralisation rate of nitrogen, however, start to increase once the stock levels

are built up. The run with a "very high" mineralisation time reaches the highest yields and production in the long run.
While the yield level changes with a variation of the SOM mineralisation time, arable land is restricted by per capita cultivable land (being constant now) and the area under maize cultivation develops similar for all tested values. Differences in production can therefore to a large extent be explained by the yield pattern (R1-, R2-, R3- and B2-loops), and the same applies for per capita total calories supply (since the area of other plants develops similarly for all the runs).
The area of maize is kept in a similar range for all sensitivity runs due to similar economic incentives (land rent). While higher yields would increase the per hectare revenue, they also increase production that decreases the producer price (B2-loop). This offsets the gained revenue from yields letting land rent develop similar for all tested runs.
The sensitivity analysis of mineralisation time indicates that the model reacts in an adequate way: in areas where soil dynamics are central it reacts in a sensitive way (e.g. yield). And in areas where soil dynamics play a less important role, the model reacts in a less sensitive way (e.g. land allocation).

Policy Testing

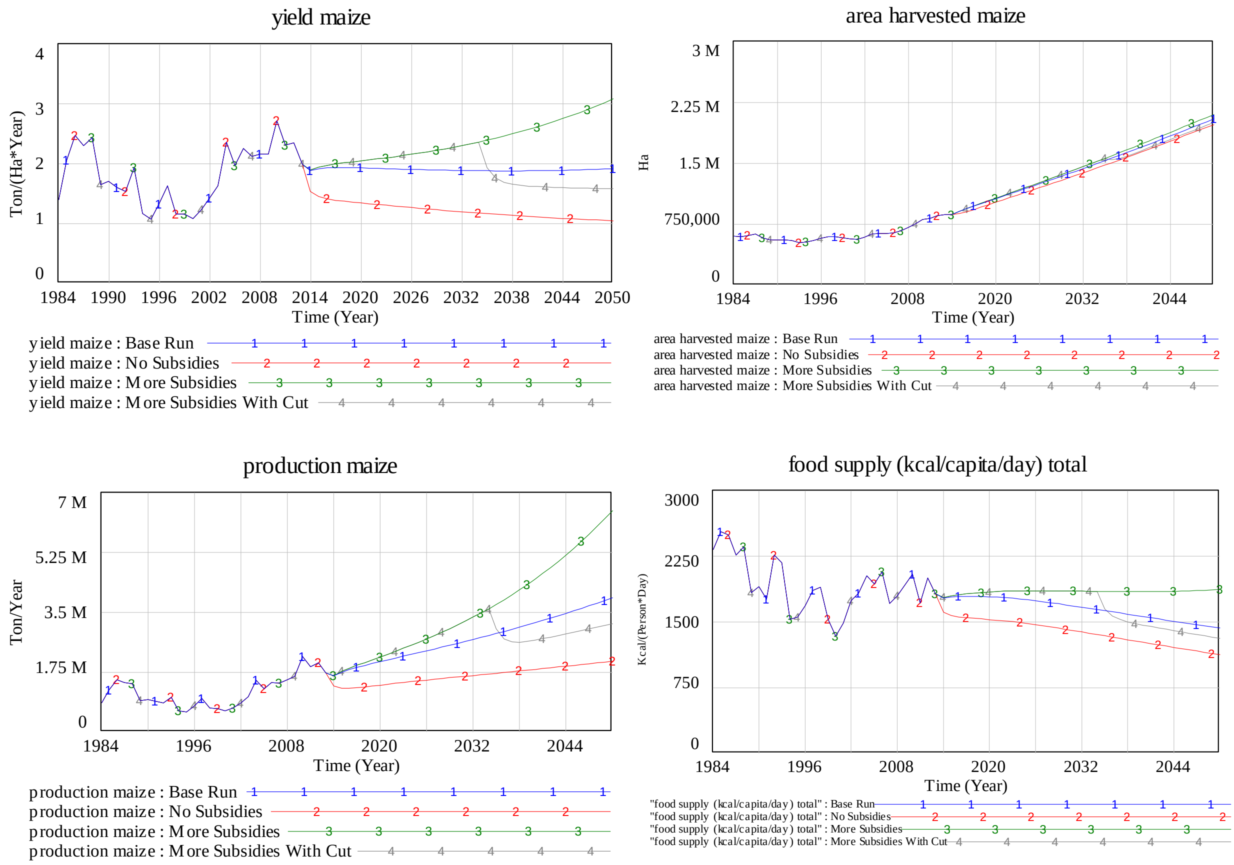
Prescription of Current Policies

As a transition from sensitivity analysis towards policy formulation I test the potential and the sensitivity of the two main food security policies that are currently in place. Therefore three variations to the base run are formulated:

- "*No Subsidies*": both the fertilizer subsidies and the food reserve subsidies drop to zero in the year 2014.
- "*More Subsidies*": both the fertilizer subsidies and the food reserve subsidies become a linear function of the population assuming that the government spends a constant amount per capita.
- "*More Subsidies with Cut*": subsidies start off equal to the "*More Subsidies*" run, however are reduced to zero in 2035.

The simulation results in Figure 13 suggest that by determining the level of subsidies the government has a policy tool to influence maize yields, production and per capita food availability. In the "*More Subsidies*" alternative total kcal availability reaches 1870 kcal per capita per day in 2050, which is a similar level to today. However, the "*No Subsidies*" alternative demonstrates that the food system reacts in a sensitive way to a total drop of subsidies causing yields, production and kcal availability falling even below the base scenario. As an intermediate alternative the "*More Subsidies with Cut*" run demonstrates - ceteris paribus - how dependent the food system is on the GRZ subsidies: because the state interventions mainly influence the R3- and B2-loops the yield drops fast when the subsidies area removed. However, due to higher yields and consequently higher organic matter soil inputs, both soil fertility stocks (soil organic carbon and nitrogen) build up higher levels from 2014 to 2035 through R1- and R2-loops compared to the "*No Subsidies*" run. Although yields drop fast after the subsidies removal in 2035, in the "*More Subsidies with Cut"* run they don't drop down to the value of the "*No Subsidies*" run because of the higher level of the soil fertility stocks.

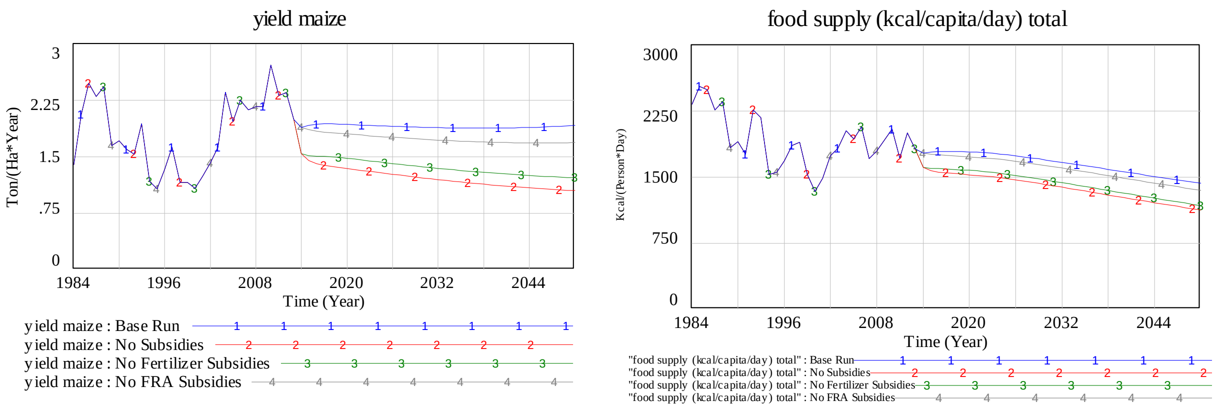
Figure 13: Runs with different subsidy levels. "No Subsidies": from 2014 on no fertilizer and food reserve subsidies are paid. "More Subsidies": the subsidies paid become a linear function of population after 2014. "More Subsidies With Cut": as "More Subsidies" but subsidies are cut to zero in 2035.



Despite high public costs associated with a "*More Subsidies*" policy, the preliminary conclusion can be drawn that such policies enhance food availability mainly in the short-term and create high dependency on the GRZ. With its focus exclusively on maize the GRZ also restricts the freedom of the agricultural sector to allocate the resources where they are most desirable. And since the level of natural resources such as soil organic carbon and nitrogen increase are built up only little under the current policies the question of alternative, log-term oriented policy options arises.

Another interesting observation concerning the current policies is that the two programs have to be evaluated differently (Figure 14). The food reserve subsidies paid to cover FRA losses have their main effect in supporting the producer price and therefore increase profitability of maize production of a few farmers (through the land rent). However, if the subsidies were left away, total calories availability decreases only little compared to the base run (-6% in 2050). On the other hand fertilizer input subsides directly increase yields (R3- and B2-loops), have a larger effect on soil fertility (R1- and R2-loops) and decrease total calories availability more if removed (-18% compared to the base run).

Figure 14: Runs to test the individual subsidies. "No Subsidies": from 2014 no fertilizer and food reserve subsidies are paid. "No FRA Subsidies": no food reserve subsidies are paid. "No Fertilizer Subsides": no fertilizer subsidies are paid.



Alternative Policy Areas

While the current policy instruments in place seem to serve short-term objectives, long-term solutions including the management of natural resources receive only little public attention. Based on the learning from the sensitivity testing above, two different areas of policies and their combination are tested in the following:

- "*Cultivable land*": a policy mix increases the number of hectares one person can cultivate. The policy mix might consist of enhanced investment into agricultural capital and increasing land access. This is implemented into the model assuming a linear increase of the number of hectares one agricultural labour force can cultivate (from 0.55 in 2014 to 0.8 hectares per person per year in 2050).
- "*Legumes*": this policy enhances the use of legumes such as alfalfa or beans as intercrops and cover of fallow land in the crop rotation scheme. It is assumed that the area under the policy regime is increasing linearly over 10 years from 0 to 33% and that annually additional 40kg of nitrogen and ca. 570kg of carbon are added per ha to the organic soil stocks.

For all policy runs it is assumed that the food reserve expenditure drop to zero in 2014 and the newly available budget is allocated into the two policy fields. Fertilizer input subsidies remain as in the base scenario. Figure 15 gives an overview how the policies work in isolation.

The "*Cultivable Land*" policy allows for more arable land and therefore also for more area cultivated with maize. Through the R4-loop the per hectare fertilizer availability is reduced resulting in lower maize yields and lower production. The low yield also reduces profitability of maize production and therefore the share of land allocated to maize (through the land rent). Proportionally more land is allocated to alternative productions resulting in increased total calories availability.

The "*Legumes*" policy adds additional nitrogen and carbon to the soil (adding to the R1- and R2-loop). While the maize yield is below the base run during the first years of the implantation phase the reinforcing loops start to gain momentum and drive both yield and production up in the long run once the soil fertility stocks increase their level. Also here total calories availability increases in the long run, however, mainly due to the increase in maize production.

Figure 15: Runs with alternative policies. “Cultivable Land”: increases the area one person can cultivate due to more capital and better access. “Legumes”: increases nitrogen and carbon input due to more legumes.

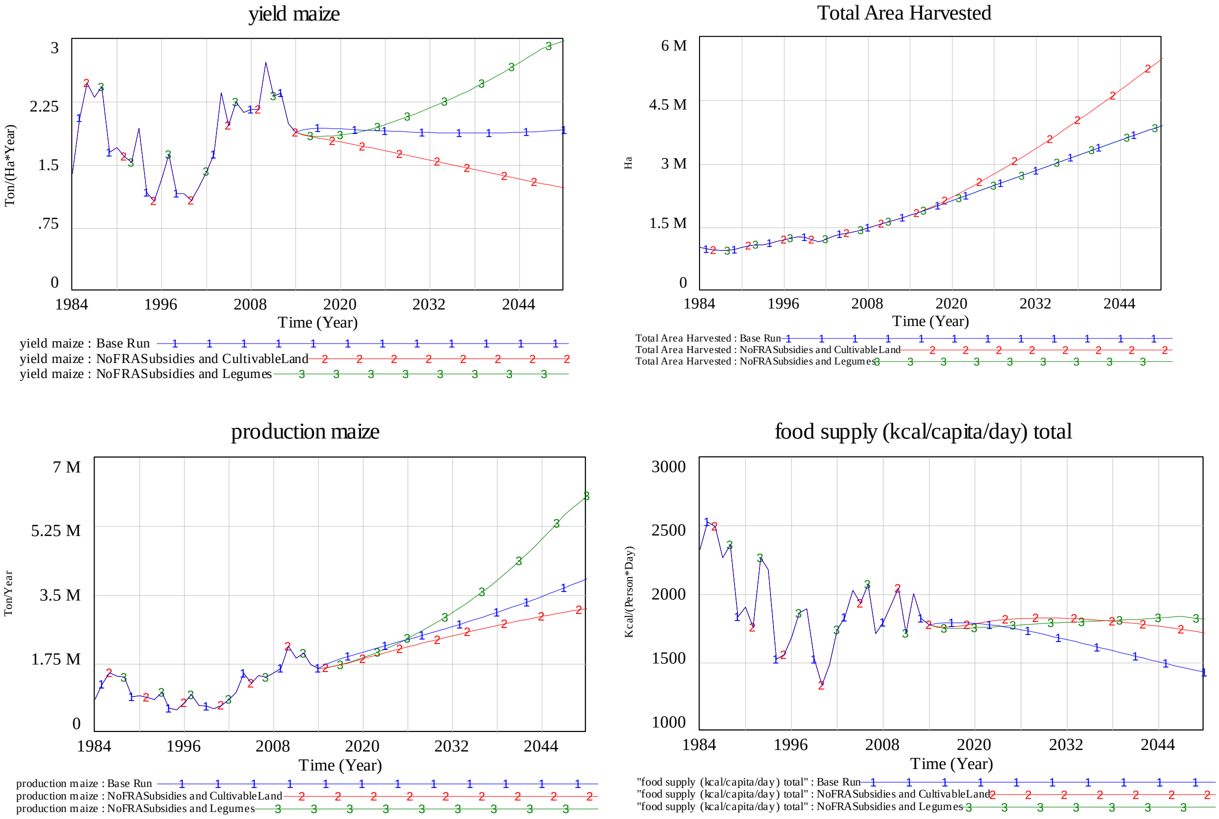


Figure 16: Policy alternatives combined and compared to the base run and the “more subsidy” run.

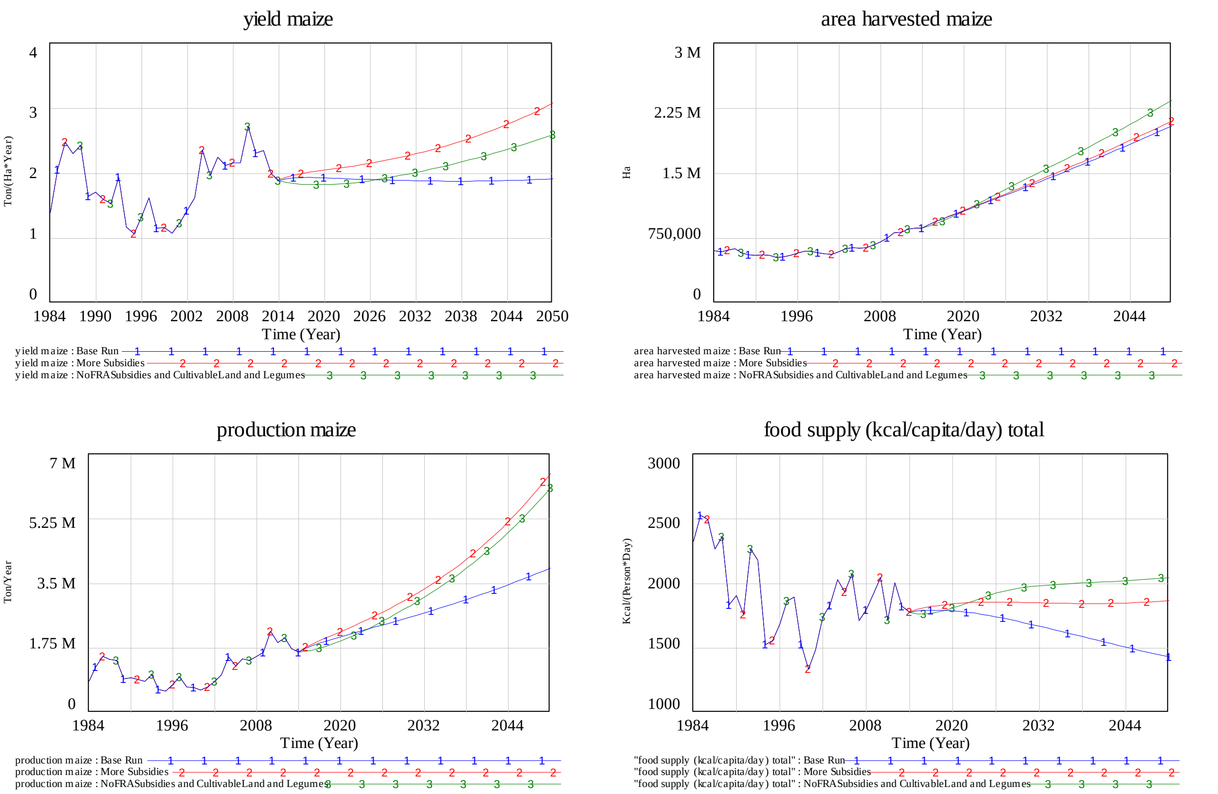
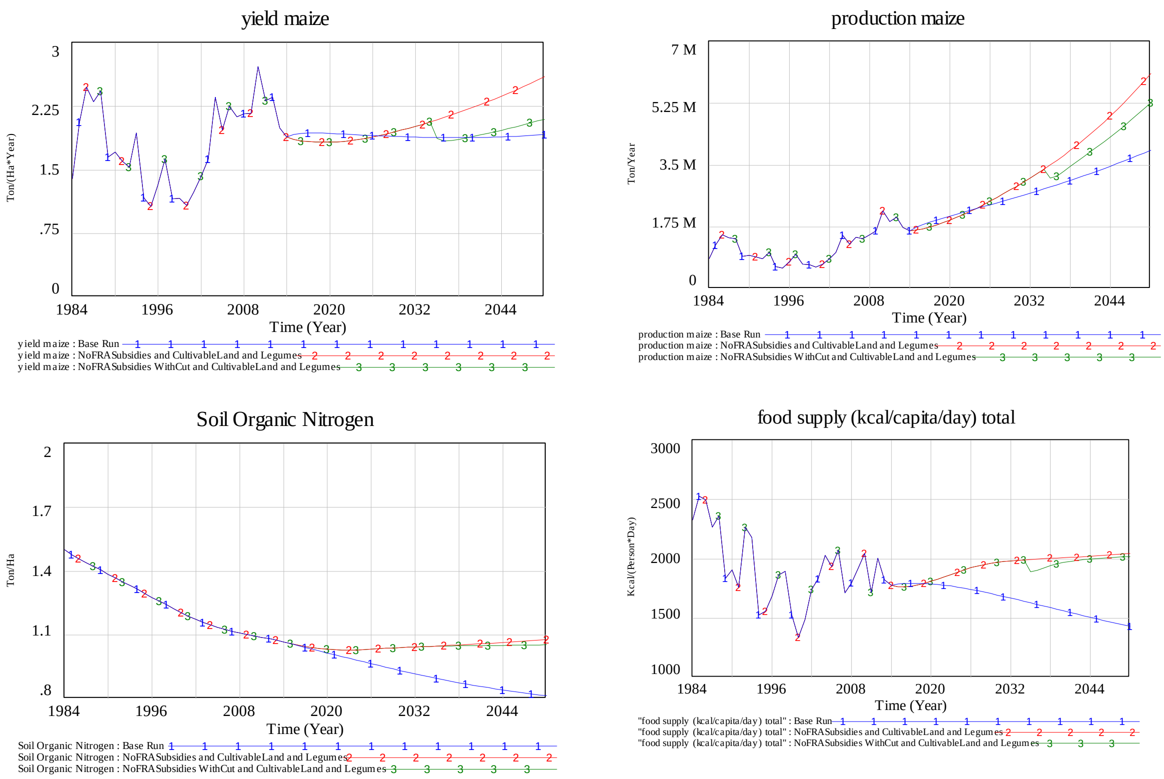


Figure 16 shows the simulation outputs of the combination of the two policies compared to the “*More Subsidies*” run. The combination of the two policies also combines the benefits of the single policy. The increased per capital cultivable land allows for more area and the addition of legumes increases soil fertility resulting in higher yields. Compared with “*More subsidies*” maize production is lower because of lower maize yields. (The maize area is only litter higher compared to the “*More subsidies*” run.) However, the arable land increases proportionally more, allowing for more non-maize production. This offsets the lower maize production and as a result total calories availability is higher than in the “*More Subsidies*” alternative in the long run.

And while in “*More Subsidies*” the annual GRZ expenditure increase from 3.5 x 10^{10} Kwatcha94 in 2014 to 10.2 x 10^{10} Kwatch94 in 2050, the fertilizer input costs remain constant at 1.9 x 10^{10} Kwatcha94 in the combined policy run. This leaves in the minimum some financial room to cover the expenses of the additional two policy areas.

Another interesting result is displayed below: for the combination of the two policies in Figure 16 a constant fertilizer subsidy was assumed. Now in in Figure 17 an additional run is presented where this subsidy is completely removed in 2035. This leads to lower maize yields and subsequently also to a lower maize production than if the subsidy was kept. However, this decrease in maize availability is offset in the long run by an increase of the area of non-maize production. And total calories availability is - after an initial decrease in 2035 - increasing to the level of the combined policy run due to an increase in arable land. This suggests that a broader policy focus leaves more freedom to the farmers and the food system to allocate resources where they are most desirable.

Figure 17: Combined policies including a cut of fertilizer subsidies in 2035 compared to combined policies without cut and the base run.



And in addition it is notable that even if the maize yield drops after the removal of the fertilizer subsidy in 2035, it still continuous to increase. This is mainly due to an increase in the soil fertility stocks (as a consequence of the legumes policy). In contrary, if subsidies are removed in the “*More Subsidy*” alternative, yields collapse (see “*More Sub-*

sidies with Cut", Figure 13). This suggests that focusing on the improvement of soil fertility strengthens the resilience of the maize system.

Conclusions

Agronomic and agricultural economic theories were combined and applied to build a bio-economic simulation model for representing a staple crop on a country level. It was specified for a low endowment and partly subsistence oriented agricultural sector facing the demand of a heavily increasing population. The model was calibrated to the case of Zambia and its staple crop maize in order to test different food security policy options. Simulation results suggest that the current input and food reserve policies theoretically have the potential to increase food availability. However, in practice they require huge public expenditure and are mainly focusing on short-term solutions (i.e. they don't focus on building up resource stocks but focus on current expenditure). Especially the food reserve policy has only a little effect on the farming sector and total food availability. This finding is in line with other studies such as Mason and Myers (2013).

Alternatively two policy options were tested focusing on natural resources such as arable land and soil fertility, combined with a constant fertilizer subsidy. While potential arable land is abundant in Zambia its use is among others limited by low endowment of farmers and land accessibility. In order to unlock this potential a policy to enhance investment into agricultural capital and land access is assumed to increase the use of arable land. This allows an increasing allocation of both, lands for maize and non-maize production.

The other resource policy focuses on soil fertility (soil organic carbon and nitrogen). Given the low stock levels of the elements and subsequently the low amount of the elements in the agricultural element cycles, the use of legumes as intercrops or for crop rotation is suggested as an additional, external source of carbon and nitrogen. This policy works out in the long run and increases the level of soil fertility stocks and therefore yields. Similar conclusions are drawn by authors such as Haggblade and Tembo (2003) or Nyanga (2012) investigating the effects of conservation farming, a practice focusing on soil fertility.

The combination of the two policy alternatives results in even higher long-term calories availability as the expensive subsidy policies. And results from Figure 17 suggest that a focus on natural resources and their sock levels might not only be cheaper than short term subsides, but even enhances the capacity of the food system to absorb shocks and therefore increase its resilience. However, the observation of Henrichsmeyer and Witzke (1991; p.302) that a growing population in low income countries doesn't leave much room for an improvement in per capital food availability is supported by the results of this study. If and with what set of policies it is possible to reach a satisfactory level of calories availability remains subject to further investigations.

Methodologically, the integration of theories from agronomy and agricultural economy to an aggregated bio-economic simulation model is found to be a useful tool to evaluate and prioritise different policy areas. The applied SD approach especially allows for a long-term perspective based on endogenous feedback mechanisms. For implementations of the suggested policies, further research is needed and further questions need to be answered. E.g. what concrete measures can be implemented in order to increase the stock of agricultural capital? What measures increase the accessibility of land? What are the consequences of an increase in arable land and is it sustainable? Or how can the leg-

umes policy fit into the production methods of Zambian farmers in order to increase acceptance?
However, the results of this study suggest that a shift away from short-term oriented food reserve policies to long-term oriented resource based policies is recommendable.

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Annex: Model Equations

Sector	Key Processes	Stocks & Key Variables	Key Concepts and Sources	Key Equations
Yield	Calculation of the annual per hectare maize production. The determinants of maize yield are nutrient and water availability, as well as soil fertility represented by soil organic matter. Nutrients are represented by nitrogen from different sources (mineral fertilizer, soil nitrogen, nitrogen inputs from animals and nitrogen inputs from legumes as a policy). The source of water is rainfall. SOM increases the share of nutrients and water taken up by the plants and therefore yield.	Soil Organic Carbon (representing SOM) Soil Organic Nitrogen Yield Maize Mineralisation Time (constant) Rainfall (exogenous) Animal N and C inputs to the soil (exogenous)	Production Function (Schilling, 2000, Heady and Dillon, 1961) Plant Residues (IPCC, 2006) Soil Organic Components (Scheffer and Schachtschabel, 2010) Mineralisation of SOM (Scheffer and Schachtschabel, 2010)	$y = A \times (1 - 10^{-c1 \times x1}) \times (1 - 10^{-c2 \times x2})$ y = yield maize, A = yield plateau, c = constant, and: $x = uptake = availableNorH2O \times ref\ uptake \times \left(\frac{SOM}{INIT\ SOM}\right)^{\varepsilon}$ $\frac{dE}{dt} = Ie,p + Ie,a - \frac{E}{tmin}$ E= soil organic elements (C,N), Ie,p = soil input of E from plant sources, Ie,a = soil input of E from animal sources. Tmin = mineralisation time of E. $\text{Ie, p} = \text{plant residues maize} + \text{other plant rsidues}$ $Plant\ residues\ maize = f(yield)$, (see IPCC, 2006)
Land	Calculation of the arable land area and derived from there the area under maize cultivation (area harvested maize). The main determinants for arable land area are the population's food need and the yields. The maize area is calculated by applying a decision rule including two goals: food security and profit seeking.	Arable Land Area Harvested Maize	Total Food Demand (Henrichsmeyer and Witzke, 1991) Goals of farmers (Henrichsmeyer and Witzke, 1991, Varian, 2007)	$Des\ areble\ land = \frac{Kcal\ need\ pop - Kcal\ net\ Iiports}{Average\ yield\ in\ calories}$ $\frac{d\ AL}{dt} = \min\left(\frac{RALD - AL}{AL\ AT} + ALOL, \frac{NUP\ AL}{AL\ AT}\right) - \text{ALOL}$ with $ALOL = \frac{Des\ OL - OL}{OL\ AT}$ Variable explanations: see text above $Share\ of\ Maize = \alpha \times \frac{LR}{INIT\ LR} + \beta$ LR: land rent, see below.
Supply	Calculation of the domestic maize supply. The	Production	Supply	$Supply = Production + NetImports$

	supply is constitutes of the annual national maize production, plus imports, minus exports. It is assumed that the whole supplied quantity is consumed before the new main harvest season starts. Production is the product from yield and the area under maize cultivation. Trade is exogenous.	Import/Export Supply	(Henrichsmeyer and Witzke, 1991)	$Production = Yield\ maize \times Area\ harvested\ maize$
Demand	Calculation of the total indicated food consumption from plant products, the indicated maize consumption and the maize demand. Both indicated consumptions depend on the population, the average dietary energy requirement (ADER) and the share from animal, plant and maize calories. The demand of maize depends on the indicated maize consumption adjusted for the level of the consumer price and maize for other use than food.	Population Per capita kcal Need Share of Plants on Diet Share of Maize on Diet Price Elasticity	Demand (Henrichsmeyer and Witzke, 1991, Varian, 2007, Sterman, 2000)	$Total\ indcated\ plant\ cunsumption = Population \times ADER \times Share\ of\ plants$ $Indicated\ maize\ consumption = Population \times ADER \times Share\ of\ maize$ $Maize\ demand = f\ (Consumer\ price, Ind\ m.consumpt.)$ (see Sterman, 2000)
Price	Calculation of the producer price and consumer price of maize. The producer price depends on the comparison between supplied and demanded quantity (supply demand ratio) and the governmental FRA price. The consumer price depends on the producer price, handling costs and food reserve subsidies.	Supply/Demand Balance Producer Price Consumer Price Food Reserve Subsidies Governmental FRA Price	Price setting (Henrichsmeyer and Witzke, 1991, Varian, 2007, Sterman, 2000)	$Indicated\ producer\ price = \left(\frac{\frac{Supply}{Demand}}{INIT\ SD\ ratio}\right)^{\epsilon}$ $Producer\ price = \min(FRA\ price, Indicated\ producer\ price)$ $Consumer\ price = producer\ price + handling\ costs - FRA\ subsidies$
Farms	Calculation of the farm income maize, the maize sales and the fertilizer expenditure. The farm income is the product of maize sales and the producer price. Fertilizer expenditures are calculated from an exogenous share of farm income maize. Maize sales depend on a profitability indicator (land	Farm Income Maize Maize Sales Fertilizer Expenditure Fertilizer Subsidies	Decision Rules (Henrichsmeyer and Witzke, 1991)	$Farm\ income = Maize\ sales \times Producer\ price$ $Fertilizer\ expenditure = Farm\ income \times Share\ to\ fertilizer$

	rent) and on a food security indicator (per capita maize supply).			$Total\ fertilizer\ expenditure = fertilizer\ expenditure + fertilizer\ subsidies$ $Maize\ sales = Production \times Share\ sold$ $Share\ sold = \frac{(\gamma \times LR + \delta) + (\vartheta \times PC\ m.supply + \theta)}{2}$
Land Rent	Calculation of the profitability indicator land rent. It represents the average profit per ha maize with regard to fertilizer expenditures. (Other expenditures are not included due to missing data.) Land rent is obtained by subtracting expenses from revenue.	Fertilizer Expenditure Yield Producer Price Maize Area	Profit (Varian, 2007) Average value product (Stephens et al., 2012)	$Land\ Rent = Revenue - Expenses = (y \times Producer\ price) - (\frac{Fertilizer\ expenditure}{AHArea\ harvested\ maizeM})$