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Abstract

Soil acidity is crucial for crop yields. Acidic soils decrease the availability of important nutrients to plants, causing lower yields. This applies to both naturally occurring nutrients and fertilizer. A well-known remedy is to provide soils with alkaline materials, like ground limestone. This raises their pH levels, increasing the availability of nutrients to the plant and eventually crop yields. So far, this practice is not widespread in Zambia, a country with largely acidic soils in agricultural areas. The agriculture of Zambia is dominated by smallholder farmers, growing predominantly maize. This paper seeks to quantify the effects on welfare that the introduction of liming would have in the Zambian smallholder maize market. For this purpose, I develop a dynamic, deterministic, open market, spatial partial equilibrium model. Solving the model requires bounded, monotonic, non-convex mixed-integer optimizations with equilibrium constraints. Model results indicate that liming in this market would reduce prices by 22.8% and increase welfare by 3.4% without international trade. With exports at 350 USD/t, the local price would drop by 16.1% and welfare would increase by 5.6% due to liming.

Keywords: Agricultural Economics, Liming, Partial Equilibrium Model, Zambia
JEL Classification: C61, O12, O33, O55, Q15

1 Introduction

In Zambia, less than 2% of smallholder farmers (farm size <20 ha) growing maize (Zea mays L.) apply agricultural lime, even though soils are predominantly acidic or extremely acidic (nationwide sample of Burke, Jayne, and Black (2016)).[1] Survey data show that 70% of farmers were not aware of the need to lime and many never did (Mitchell, 2005). More recent anecdotal evidence also suggests that smallholders' insufficient knowledge of the soil deacidifying benefit of liming may cause this low adoption rate (Burke, Jayne, and Black, 2016). Jayne and Rashid (2013) analyzes sub-Saharan African agricultural policies and suggests initiatives for improved soil fertility. Among other measures, this includes addressing soil acidity and the deacidification of the Brazilian Cerrado region is given as a successful example. Jayne and Rashid (2013) sees soil testing and educational campaigns targeting farmers' knowledge gap as crucial for this measure.

Although qualitatively advisable, these campaigns face a problem: the desire of politicians to tangibly demonstrate their support to their constituents makes input subsidy programs (ISPs) more popular in the region (Jayne and Rashid, 2013).[2] Different from ISPs, a government intervention in the form of an educational campaign requires a substantial amount of time until benefits manifest (Jayne and Rashid, 2013). This deferral of benefits and uncertainty over their size may decrease the value of such an intervention in the eyes of politicians.

This paper quantifies the benefits of a government intervention to make the virtues of

[1](Mason, Jayne, and Mofya-Mukuka, 2013) state, that in the 2010-11 agricultural season only 0.4% of Zambian smallholder households applied lime.

[2]This study, similar to (Jayne and Rashid, 2013), considers ISPs to subsidize only fertilizer and not lime.

agricultural liming common knowledge in Zambia. The intervention compliments existing ISPs for fertilizers. By assumption, the government covers all potential costs of the intervention. The benefits are computed as reductions in the local price (p) of maize, caused by higher productive efficiency from liming. Also, related increases in welfare (WF) on the maize market are calculated, as a measure for the induced change in well-being of both consumers and producers combined. This way, I attempt to provide valuable information as basis for government decisions on future support schemes to reduce poverty and food insecurity and to enable growth.[3]

The political importance of maize in Zambia stems from its status with both producers and consumers. Combined, over 1 mn smallholder households account for >92% of maize output in the agricultural season 2010-11 (CSO, 2016; Zambia Ministry of Agriculture, 2011). Maize supplies around 60% of caloric intake in Zambia, making it the dominant food crop (Mason and Myers, 2013). Sitko et al. (2017) states that the price of maize is considered an indicator of the effectiveness of the Zambian government. Sitko et al. (2017) illustrates this with food riots in 1986 after a spike in prices of maize meal, believed to have been caused by a discontinuation of maize subsidies. The riots led to a departure from austerity measures imposed by the IMF, which provoked a withdrawal of IMF funding the following year, succeeded by a crash of the Zambian economy, bringing nearly 30 years of single party rule to an end (Sitko et al., 2017).

With this in mind, I assume that the government wants to ensure the effectiveness of ISPs on the market for maize. To that end, it is important to understand the impact of soil acidity (measured in pH) on nutrient availability. Soil acidity between 5.0 and 8.0 allows the successful cultivation of maize, while the optimal range is 6.0 to 7.2 (Verheye, 2010). The accessibility of important nutrients to plants declines with rising acidity, i.e. decreasing pH (Figure 1). Thus, nutrients added as fertilizers are more likely to be wasted the more

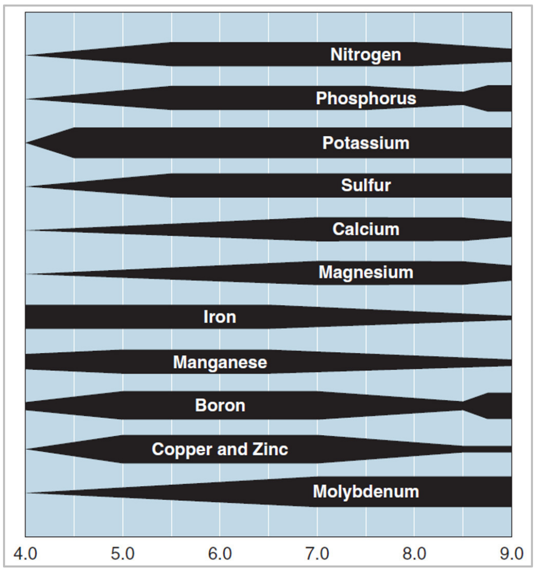

Figure 1: *nutrient availability by soil pH (Fernández and Hoeft, 2017)*

acidic soils are. On extremely acidic soils (pH <4.5) up to 70% of fertilizer may be wasted, predominantly phosphate (Mosaic Company, 2017). It appears reasonable to prevent such waste, especially since no established alternatives for fertilizer from mined phosphate exist and global phosphate mining is concentrated among few producers (cf. Gilbert (2009)). At least two effects inhibit plants from accessing nutrients in acidic soils (Fageria and Baligar, 2008): first, nutrients react with aluminum or iron and become unusable to plants. Second, exchangeable and soluble aluminum and manganese increase with acidity. High concentrations of these are phytotoxic, curbing root growth.

Figure 2 shows that Zambian smallholders grow maize mostly on acidic soils. By the definitions above, 45% of the area of production is extremely acidic, 39% is deemed adequate for maize growing, but only 1% is in the optimal range of soil pH.

Burke, Jayne, and Black (2016), as well as already Burke (2012) more extensively, argue that the positive effect of liming on soil acidity is known to Zambian agronomists. The et al. (2006) examines the relationship of acidic tropical soils and maize cultivation based on experimental data, recommending liming alongside the use of acid soil-tolerant cultivars.

[3] Cf. Collier and Dercon (2014) for a discussion on the role of smallholder agriculture in poverty reduction and economic growth policies.

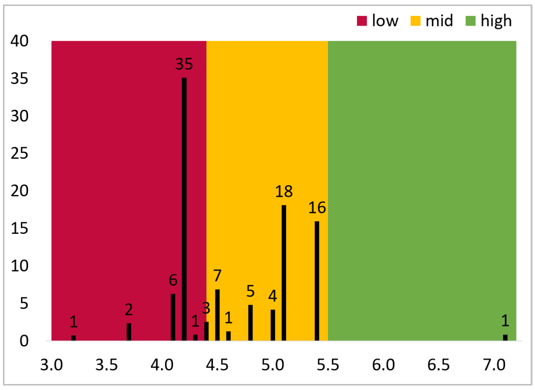

Figure 2: *sample distribution by soil pH,*
in percent of sample area
data: Burke, Jayne, and Black (2016)

This paper contributes to ongoing research into soil management for the benefit of agriculture in regions in development. For example, Nakhumwa and Hassan (2012) models dynamic decisions regarding general soil erosion for the smallholder maize market in Malawi, focusing on the supply side, disregarding consumer surplus and endogenous price effects. I extend the literature[4] with a country-wide model including market access costs and external trade. These extensions enable an overall economic view of a self-sufficient country with the capacity to produce for the global market.

The remainder of the text is organized as follows: Section 2 gives background information on the management of soil acidity and agricultural liming. Section 3 outlines an economic model for liming in the Zambian market for smallholder maize. Section 4 describes the data used in the model. Section 5 explains how the model is solved. Section 6 analyzes the outcomes of the model and Section 7 concludes and gives an outlook.

2 Management of Soil Acidity

Traditionally, Zambian smallholders coped with acidic soils, especially in the high rainfall northern areas of the country, via a shifting slash-and-burn cultivation, locally known as Chitemene (Mitchell, 2005; Shitumbanuma et al., 2015). In this approach, land is cleared from the natural bush vegetation, which is then dried and burnt, so the ashes can add nutrients to the soil they are worked into and raise its pH level (Mitchell, 2005; Shitumbanuma et al., 2015). The cleared area is cultivated for 4 to 5 years and then abandoned for 20 to 30 years to recover, but due to population growth and related pressure on food production, this traditional approach is no longer sustainable (Mitchell, 2005; Shitumbanuma et al., 2015). Smallholders moved on from Chitemene[5] to a mix of traditional and modern farming practices, where burning of fields before planting is still common (Mitchell, 2005; Umar et al., 2012; Conservation Farming Unit, 2011). Negative effects of the traditional burning of fields are the reduction in soil carbon stocks and emissions of this carbon into the atmosphere (CIAT and World Bank, 2017).[6]

The benefit of liming acidic soils include higher pH levels and better soil structure (Bolan et al., 2008). Both result in higher crop yields. Thus, liming is an alternative to traditional forms of acidity management and combined with fertilizer use may replace them. Apart from higher yields due to less acidic soils, a switch to liming could eliminate the practice of burning fields with its negative effects. Rengel (2003) describes potential harm from overliming, namely the chance of a deficiency in manganese and zinc at high pH levels. The reaction of lime with acidic soil also emits CO_2 (West and McBride, 2005). I focus on the conventional effect of agricultural liming: raising soil pH to improve the efficiency of agricultural production.

To simulate the benefit of liming it is necessary to quantify the relationship between the amount of applied lime and the increase in pH and that between pH and maize output. For the former relationship, I consider liming recommendations based on initial pH level, target pH level, and soil texture from Vossen (2016). Soil texture correlates with cation exchange capacity (CEC), which makes

[4] e.g. Øygard (1986) develops a simple farm level model for liming decisions in Zambia.

[5] In the agricultural season 2010-11, less than 1% of maize growing households prepared fields this way (CSO, 2016).

[6] Burning of grasslands makes up around 60% of greenhouse gas (GHG) emissions from agriculture in Zambia in 2012 (CIAT and World Bank, 2017).

soils less sensitive to pH change and liming (Sishekanu et al., 2015). For the effect of lime on maize output, I use an empirically estimated yield function for smallholder maize in Zambia (Burke, Jayne, and Black, 2016), which depends on soil pH and reference soil groups (RSGs) of the Food and Agriculture Organization of the United Nations (FAO). Burke, Jayne, and Black (2016) aggregates RSGs by texture characteristics, which I map to the texture categories in Vossen (2016) (e.g. Arenosols grouped into "sandy and less developed soils" mapped to "sand and loamy sand").[7]

In this paper, all lime is ground limestone (calcium carbonate, $CaCO_3$). Neither quicklime (CaO) nor hydrated lime ($Ca(OH)_2$) are considered given their prohibitively high production costs (West and McBride, 2005). Resources of carbonate rock, e.g. dolomite, suitable for agricultural lime production exist throughout Zambia, even in regions with acidic soils (Mitchell, 2005). This availability and the feasibility of setting up small-scale local lime production within farming districts allows nation-wide supply of lime (Mitchell, 2005). Lime is assumed to be fine ground (approx. 150 μm or 100 mesh), as deemed reasonable for local production (Mitchell, 2005). The large surface of fine lime guarantees quick reaction with soil.

This paper considers not only elevating soil pH, but also maintaining it at the desired level. While nitrogen (N) fertilizer application may acidify soils, liming at a rate of 3.6 kg/kg of N fertilizer can neutralize the acidifying effect of the fertilizer (McLaughlin (2010), cf. Peters and Kelling (1998)).

3 Model

The object of this analysis is the Zambian market for smallholder maize. If not otherwise qualified, all values refer to it.

The purpose of the analysis is to evaluate potential effects on WF from the adoption of agricultural liming in the Zambian market.[8] To focus on this market, a fundamental partial equilibrium model is used. Optimal input and output choices are quantified dependent on global prices ($g \in G$), liming investment scenarios ($s \in S$), and modeled period ($t \in T$).

Zambia has a history of frequent government interventions in the maize market (Sitko et al., 2017). I model tariffs, subsidies, and official recommendations on fertilizer rates as exogenous, constant government actions.

3.1 Perfect Competition

Many producers[9] and consumers, each with low individual capacities, trade a homogeneous good, maize, at a uniform price. Information on prices and capacities is transparent. No externalities exist. Production factors are mobile in the market. Due to these characteristics, perfect competition is assumed and profit maximization leads to a WF optimal outcome.

3.2 Trade

The model allows trade, while treating Zambia as a small country, i.e. price taker on the global market. Global prices ($g \in G$) are exogenous. Trade is costly because of transport and tariffs. It occurs if the absolute value of the difference between global price and a hypothetical Zambian equilibrium price in isolation (absence of trade) exceeds the costs of trade (Figure 3). The latter are exogenous, while the hypothetical local price in isolation is endogenous and depends on the local production functions. Liming affects these functions.

In the model, trade changes the effective local price, increases, and redistributes WF compared to isolation (Figure 3). WF is the integral under the active demand curve (D) and above the active supply curve (S).[10] It combines consumer surplus (CS) and producer

[7] Solonetz, Fluvisols, Phaeozems, and Planosols are aggregated into "other soils". Uniformly neutral Solonetz (pH of 7.1 for all observations) needs no liming or mapping to a texture category and is considered independently. The latter three acidic RSGs are mapped to Vossen (2016) based on International Union of Soil Sciences Working Group WRB (2015) (see data appendix).

[8] I disregard distributional issues.

[9] Over 1 mn households grew maize in the agricultural season 2010-11 (CSO, 2016).

[10] Demand is modeled in Section 3.4. A supply curve is not explicitly formulated but rather a result of the optimization of producer surplus (Section 3.10).

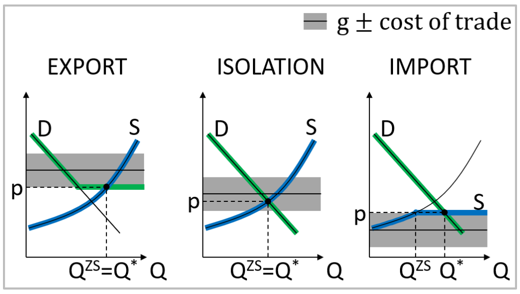

Figure 3: *equilibria with costly trade, active curves colored*

surplus (PS). CS is the integral under D and above p, while PS is the integral under p and above S, i.e. the combined profit of all producers.

In both trade cases, compared to isolation, a larger equilibrium quantity increases WF. In the export case, the increase in PS exceeds the decrease in CS, while in the import case, CS increases more than PS decreases.

CS is generated by all local consumption regardless of origin of the consumed maize (import or local production). PS stems from all local production regardless of destination of the produced maize (export or local consumption). Other CS and PS on the world market are disregarded.

3.3 Dynamics

The model is dynamic and deterministic. It simulates the nature of liming with an investment phase in one year and a subsequent benefit phase of multiple years. It has an infinite time horizon divided into discrete one-year-periods (t). Markets are assumed to clear in each period.

The periods resemble the agricultural season of Zambia, starting with planting in October. Due to superior data availability (Section 4) the Zambian agricultural season of October 2010 through September 2011 is defined as reference for the initial model period (t_0) and used to measure the goodness of fit of the model (Section 6.1).[11]

The model is evaluated in the first month of the reference season, October 2010. All future monetary values are discounted to this point in time with the real annual interest rate. Parameters from the reference season remain constant over the modeled periods and can be interpreted as expected values. Production related costs occur in October, revenues and related costs in the following August.

An appropriate measure to evaluate WF in a multi-period-setting is the cumulative present value of WF, i.e. total WF (TWF). It sums current and all discounted future per period WF.

[11] Among others, CSO (2016) provides valuable data for the reference season.

3.4 Demand

The local demand (Q^{DZ}) linearly dependent on p is given by:

$$Q_p^{DZ} = Q_{sat} + slope^{DZ} \cdot p \qquad (1)$$

The slope of local (Zambian) demand ($slope^{DZ}$) stems from multiplying the price elasticity of demand (ε) with the ratio of the equilibrium quantity of the reference season (Q_{ref}) and the equilibrium price of the reference season (p_{ref}). The intercept is a parameter for the market saturation quantity (Q_{sat})[12].

With the local market modeled as a small country, demand from the global market (Q^{DG}) is perfectly elastic:

$$Q_{g,p}^{DG} = \begin{cases} \infty & \text{if} \quad g - c_{exporting} > p \\ 0 & \text{if} \quad g - c_{exporting} \leq p \end{cases} \qquad (2)$$

Q^{DG} depends on p, g, and the constant cost of exporting ($c_{exporting}$).

The maximum of Q^{DG} and Q^{DZ} defines demand (Q^D), creating a kinked Q^D curve in case of exports (Figure 3). Since individual producers are price takers, Q^D is exogenous to their decisions.

3.5 Producers

Individual, atomistic producers are distributed over a range of conditions of production, including soil texture and acidity, which influence their yield and cost functions (Sections 3.7 and 3.9 respectively). To limit

[12] $Q_{sat} = Q_{ref} - slope^{DZ} \cdot p_{ref}$

computational complexity, atomistic producers with equal soil conditions are aggregated into a set of eight heterogeneous representative producers ($i \in I$) (Section 4.2). They maximize their expected profits by choosing their input and output quantities at a given price ($p \in P$). The producer surplus as the combined profit of all producers ($PS_{g,p,s,t}$) is the objective variable of the combined maximization problem of producers in each period (Section 5.1).

Producers have perfect knowledge and foresight of the market, so production is efficient.

3.6 In- and Outputs

Inputs are capital, labor, and land. Ratios of labor to land and of capital (excluding fertilizer) to land are fixed, thus labor and some capital are implicitly chosen while choosing how much land to employ, i.e. the share of area used ($x^{\alpha}_{i,g,p,s,t}$).

Fertilizers (two types: top dressing and basal (Section 4.2)) are capital inputs chosen independently from $x^{\alpha}_{i,g,p,s,t}$. Eligible smallholders receive subsidized fertilizer. Thus, producers can choose not only between both fertilizers, but, up to a limit, also between the subsidized and market versions thereof. The four elements of the vector of fertilizer rates ($\boldsymbol{x}^{f}_{i,g,p,s,t}$) stand for applied rates of both fertilizers bought each at full market prices and subsidized prices.

Producers face the additional choice of whom to sell their maize to. Produced quantities depend on the set of buyers (J), which includes on- and off-farm private domestic buyers, the Food Reserve Agency of the Zambian Government (FRA), and foreign buyers. The FRA buys maize from eligible smallholders at subsidized prices above the competitive market price and resells it at an increased competitive price later in the season. Given the FRA sells at a profit (Mason and Myers, 2013) and assuming an efficient process, this program redistributes WF from consumers to producers. Even though the FRA publishes neither prices nor quantities at planting time, the deterministic nature of the model assumes that producers form adequate believes about them. Also, prices have maintained stable over seasons. Quantities sold to the different buyers are the four elements of the vector of quantities of maize sold to different buyers ($\boldsymbol{x}^{q}_{i,g,p,s,t}$).

In summary, each i maximizes his profit with respect to nine decision variables, categorized into three groups: $x^{\alpha}_{i,g,p,s,t}$, $\boldsymbol{x}^{f}_{i,g,p,s,t}$, and $\boldsymbol{x}^{q}_{i,g,p,s,t}$.

All decision variables are non-negative and all but the quantity of exported maize are parametrically bounded above. Exports are bounded above only by production constraints (Equation 7).

$$0 \leq x^{\alpha}_{i,g,p,s,t} \leq 1 \tag{3}$$

$$0 \leq \boldsymbol{x}^{f}_{i,g,p,s,t} \leq \bar{\boldsymbol{x}}^{f} \tag{4}$$

$$0 \leq \boldsymbol{x}^{q}_{i,g,p,s,t} \leq \bar{\boldsymbol{x}}^{q}_{i} \tag{5}$$

Usage of area is assumed to be limited at its level in the reference period (Equation 3). Arable land is unlikely to be a limiting factor for production capacity in Zambia (cf. Export.gov (2017)). Given low mechanization, not land itself, but rather the supply of capital to cultivate it limits production. Yet, due to data availability, cultivated land is used as a proxy for the exogenous limit of this input.

Reference period subsidy levels limit the application of subsidized fertilizer and the government recommendation on total fertilizer rates sets an upper bound on the application of each fertilizer bought at full price (Equation 4). Government recommendations on fertilizer rates (200 kg/ha (Mason, Jayne, and Mofya-Mukuka, 2013)) cater to the need of maize plants for a balanced nutrient supply.[13]

Equation 5 institutes bounds for sold quantities. The total quantity sold to the FRA may not exceed its reference level, allocated to producers weighted by area (their share of planted area in the reference season). On-farm sales, which include own consumption, are limited at the area weighted difference of total production and sales to the FRA in the reference season. Off-farm sales have to be smaller than or equal to Q_{sat}.

[13] cf. also Donovan et al. (2002) and Saïdou et al. (2018)

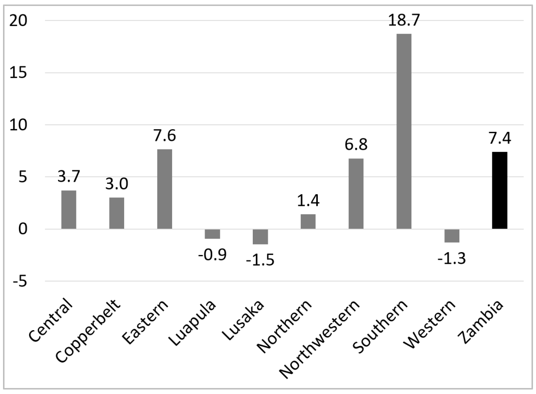

Figure 4: *Average difference of fertilizer rates, district data weighted with area planted to maize, in percent of top dressing rate data: CSO (2016) for 2010-11*

As recommended, both fertilizers have similar application rates in the reference period (Figure 4). The recommendations limit producers' input choices. In the model, they restrict divergence of fertilizer rates to a 15% range:

$$\sum_{\kappa=1}^{|K|} x^f_{i,g,p,s,t,\phi,\kappa} \leq \sum_{\kappa=1}^{|K|} x^f_{i,g,p,s,t,\psi,\kappa} \cdot (1 + range) \tag{6}$$

$$s.t.\ \psi, \phi \in \{basal, top\ dressing\};\ \psi \neq \phi$$
$$\kappa \in K = \{subsidized, full\ price\}$$

Equations 3 to 6 are linear and monotonic.

3.7 Production

A producer's production may not fall short of the sum of his sales to all buyers. This constraints production (Equation 7) in a market wide profit maximization (Equation 9). Increased fertilizer use shows diminishing returns (Burke, Jayne, and Black, 2016). Hence, the yield function (parenthesis in Equation 7) is concave and quadratic. It consists of the fertilizer variables, the coefficient matrix of the quadratic terms ($\boldsymbol{A}$), the producer specific coefficient vector of the linear terms ($\boldsymbol{\beta}_{i,s,t}$), and a producer specific yield shifter ($\gamma_{i,s,t}$)[14]. Multiplying the yield function with $x^\alpha_{i,g,p,s,t}$ and the constant individual area of a producer (a_i) completes the quasiconcave, cubic production function (*RHS* of Equation 7), which describes the hypograph above zero of the yield function. The constraints are multiplicative concave and monotonic on the domain set by the bounds.

$$\sum_{j=1}^{|J|} x^q_{i,g,p,s,t,j} \leq \left(\frac{1}{2} \boldsymbol{x}^f_{i,g,p,s,t}{}^T \boldsymbol{A} \boldsymbol{x}^f_{i,g,p,s,t} + \boldsymbol{\beta}_{i,s,t}{}^T \boldsymbol{x}^f_{i,g,p,s,t} + \gamma_{i,s,t} \right) \cdot x^\alpha_{i,g,p,s,t} \cdot a_i \tag{7}$$

3.8 Lime

Lime is an additional input. After producers apply it, lime improves their production functions for future periods. By assumption, producers are unaware of this and learning about the benefits of liming is prohibitively expensive for them.[15] Therefore, they disregard lime as an input. Considering lime in this way maintains the outcome established above (Section 3.1). Yet, the outcome is no longer necessarily WF optimal, if an exogenous intervention can introduce universal knowledge on liming. If investments in liming lead to net-increases in WF, the introduction of this technology is socially desirable.

In t_0, producers in the lower two pH groups (Figure 2) make a one-time, discrete choice whether to ascend to one of the higher two groups via liming.[16] In all following periods, they belong to their group of choice with a correspondingly higher yield curve, due to higher $\boldsymbol{\beta}_{i,s,t}$ and $\gamma_{i,s,t}$ (Equation 7).[17]

The decision to lime is costly. I consider two forms of liming: initial and ongoing. Initial liming is a single application of lime to raise soil pH to the desired level. It causes sunk,

[14] $\gamma_{i,s,t}$ groups characteristics of the yield function of Burke, Jayne, and Black (2016) that are not interacted with fertilizer rates or pH. It contains, among others, information on soil groups, weather, and tillage techniques.

[15] This is based on the survey data from Mitchell (2005) and the anecdote in Burke, Jayne, and Black (2016).

[16] Producers with neutral soils do not suffer from acidity and hence do not lime.

[17] Meyer and Volk (1952) mentions large applications of lime (>7 t/ha) to acidic soils raising pH levels above the thresholds of Burke, Jayne, and Black (2016). These applications raise pH considerably even within the first months, before reaching final pH levels (cf. also Peters and Kelling (1998) for finely ground lime).

positive investment ($invest_{i,s,t}$) for a_i in t_0.[18] Since the application of N fertilizer acidifies soils, ongoing soil management is necessary to maintain the pH level of the soil.[19] Comparable to traditional practices, which offer a certain stability at the initial pH level, ongoing liming maintains the elevated pH levels without having to move to new fields. By assumption, producers who are convinced of the benefits of liming and invest in an initial application, will continue to manage soil acidity with lime rather than traditional practices. Thus, on initially limed soils, costly ongoing liming takes place in all following periods, slightly increasing the variable cost of applying N fertilizer.

3.9 Cost Functions

Equation 8 describes the total costs ($c_{i,g,p,s,t}$) of producers, including $invest_{i,s,t}$, the cost coefficient for used area (c_i^a), the cost coefficient vector for fertilizers ($\boldsymbol{c}_{i,s,t}^f$), and the cost coefficient vector for sold quantities ($\boldsymbol{c}_i^q$):

$$c_{i,g,p,s,t}(x_{i,g,p,s,t}^{\alpha}, \boldsymbol{x}_{i,g,p,s,t}^{f}, \boldsymbol{x}_{i,g,p,s,t}^{q}) = x_{i,g,p,s,t}^{\alpha} \cdot a_i \cdot \left({\boldsymbol{c}_{i,s,t}^{f}}^T \boldsymbol{x}_{i,g,p,s,t}^{f} + c_i^a \right) + {\boldsymbol{c}_i^q}^T \boldsymbol{x}_{i,g,p,s,t}^{q} + invest_{i,s,t} \tag{8}$$

$c_{i,g,p,s,t}$ includes both planting time expenses and marketing expenses discounted to the beginning of the planting season.

Costs of lime for maintenance and its transport elevate $\boldsymbol{c}_{i,s,t}^f$ from t_1 onwards. Potential cost reductions in c_i^a from discontinuing traditional management of soil acidity are assumed to be negligible and offset by the similarly negligible cost of applying lime during field preparation.

[18] In addition to a_i, an area equivalent to a fraction of a_i is kept fallow every period. This fraction of a_i receives the initial liming in the second model period (t_1).

[19] I disregard acidification from crop extraction and rain leaching. The former is economically insignificant, demanding liming at approx. 2.4 kg/t of maize harvested, (own calculation based on Pierre and Banwart (1973)). Price changes for maize would be <0.1%. Rain leaching is ignored, since soil exposed to pure rain (pH = 5.67) gravitates to a pH of 5.2 in the long term (Robson, 1989). Most Zambian soils would benefit from this. Yet, rain may be acidic in industrial areas, e.g. in Copperbelt Province (pH = 4.7 in Kitwe) (Tidblad et al., 2007).

The functions are monotonic and bilinear, since producers consider quantities of fertilizers, determined by the product of $\boldsymbol{x}_{i,g,p,s,t}^f$ and $x_{i,g,p,s,t}^{\alpha}$.

3.10 Objective Function

$PS_{g,p,s,t} : \mathbb{R}_+^{72} \rightarrow \mathbb{R}_+$ takes individual profits as the difference of individual revenues ($rev_{i,g,p,s,t}$) and $c_{i,g,p,s,t}$ and sums them over I. The dot products of the price vector for sold quantities ($\boldsymbol{p}^q$) and of $\boldsymbol{x}_{i,g,p,s,t}^q$ defines $rev_{i,g,p,s,t}$ as linear functions.

$$PS_{g,p,s,t} = \sum_{i=1}^{|I|} {\boldsymbol{p}^q}^T \boldsymbol{x}_{i,g,p,s,t}^q - c_{i,g,p,s,t} \tag{9}$$

Equation 9 is monotonic and bilinear due to $c_{i,g,p,s,t}$.[20]

3.11 Local Demand Constraint

The sum of supply from all local producers to all local buyers (Q^{SZ2Z}) may not exceed Q^{DZ}.

$$\sum_{i=1}^{|I|} \sum_{j=1}^{|J|} x_{i,g,p,s,t,j}^q - Q_p^{DZ} \leq 0 \tag{10}$$

$$s.t.\ j \neq export$$

In case of imports, slack in this constraint equals the import quantity. The constraint is linear and monotonic.

3.12 Liquidity Constraints

Producers' limited budgets create liquidity constraints (Equation 11). Costs cannot exceed respective budgets, i.e. liquidity ($l_{i,g,p,s,t}$). The parameter for initial liquidity in t_0 ($l_{i,g,p,s,0}$) grows with retained profits in each period.

$$c_{i,g,p,s,t} - l_{i,g,p,s,t} \leq 0 \tag{11}$$

These constraints are monotonic and bilinear due to $c_{i,g,p,s,t}$.

[20] Fixed investment costs are not stated, since they are only relevant for the optimization in the liquidity constraint (Equation 11), not in the objective function.

3.13 Interventions for Lime

Under these circumstances, the government can increase TWF via liming in two steps: First, it can intervene by making producers aware of the benefits of liming. With such updated information, producers will maximize their profits by choosing adequate investment levels for lime. Before investments take place and after assessing if individual profit maximizing investments are TWF optimal, the government may intervene a second time to guarantee TWF optimal investments (e.g. by manipulating costs of lime).

To quantify the TWF impact of these interventions, I consider two states of the model: The first state is a baseline before the interventions, where no producer has knowledge on liming and acquiring this knowledge is prohibitively costly, so no one limes in the TWF optimum. The second state is a counterfactual, where the government has eliminated the cost of knowledge on liming with an educational and soil testing campaign, so every producer chooses an adequate investment in liming. In both states TWF is computed. The WF potential of liming is the difference between the TWF of a counterfactual with TWF optimal liming and TWF of the baseline without liming.

It is possible that the counterfactual liming investments as chosen by the producers are not TWF optimal, i.e. they are not incentive compatible with the social optimum, requiring the second government intervention. Incentive compatibility is tested by comparing the benefit of each i (TPS_i) in the TWF optimum with the respective TPS_i when i's investment deviates from the TWF optimal investment. TPS_i is defined by the individual cumulative present value of PS, i.e. total PS (TPS). When TPS_i is highest in the TWF optimum for each i, then individual profit maximizing investment choices are incentive compatible with the social optimum and the TWF optimum is an equilibrium.

4 Data

Data used in the model is collected from various sources, all of which are stated in the data appendix. This section introduces the principal sources.

All monetary values are denominated in October 2010 US dollars (USD). If necessary, original monetary data are inflated, deflated and converted accordingly.[21] Exogenous data are constant over time. The real annual interest rate is r = 23.57% p.a.[22]

4.1 Equilibrium

The reference market equilibrium is at Q_{ref} of 2.718 mn t (CSO, 2016) and p_{ref} of 189.42 USD/t (used for Q_{sat}, Equation 1). This price is a season average of monthly retail prices of all Zambian provincial capitals (Famine Early Warning System Network, 2012), weighted with the populations of the provinces (CSO, 2012).

In the reference season, the FRA purchased 1.752 mn t (Mason, Jayne, and Myers, 2015) (64%) of all smallholder maize production (CSO, 2016) (Equation 5) at an above market price of 263 USD/t (Mason, Jayne, and Myers (2015) converted to USD) (Equation 9).

By assumption, the own price elasticity of demand for maize in Zambia ($slope^{DZ}$, Equation 1) equals the respective elasticity in South Africa (average from elasticity of demand for food and feed) at -0.19. Maize is the dominant staple crop in both of these southern African countries (Mason and Myers, 2013; Gouse et al., 2005).

4.2 Production

Burke, Jayne, and Black (2016) provides a set of panel data with a range of conditions of production and estimation coefficients for a yield function of smallholder maize in Zambia. Among others, conditions of production

[21] For exchange rates see Bank of Zambia (2015), for US inflation see Organisation for Economic Co-operation and Development (OECD) (2017), and for Zambian inflation see World Bank (2016b).

[22] r is based on the nominal interest rate of 30% p.a. as experienced by Zambian smallholders (Haggblade, Kabwe, and Plerhoples, 2011) and the Zambian 2011 inflation rate of 6.43% p.a. (World Bank, 2016b). Future periods ignore inflation, i.e. all future values are in October 2010 USD. Since future values are mainly used to generate cumulative present values, inaccuracies caused by the neglect of inflation are assumed to be minimal. The neglect may cause problems if inflation rates for goods in the model vary significantly.

depend on soil texture and acidity. Individual, atomistic producers are distributed over this range of conditions of production. This study includes five categories of soil texture: clay loam, sand and loamy sand, muck, sandy loam, and Solonetz. The latter is neutral and therefore irrelevant for deacidifying liming investments.[23] Soil acidity is defined by initial pH levels and clustered into three groups: low, mid, and high pH with thresholds at 4.4 and 5.5 (Figure 2) (cf. Burke, Jayne, and Black (2016)). There are eight soil types, i.e. unique combinations of textures and initial pH groups (Table 1). Representative producers ($i \in I$) originate from these soil types.

	low	mid	high
clay loam	41.9	26.3	-
loamy sand	1.5	21.2	-
muck	1.7	6.1	-
sandy loam	0.6	-	-
Solonetz	-	-	0.8

Table 1: *share of area by soil texture and pH, in percent*
data: based on Burke, Jayne, and Black (2016)

I model the production of one good, maize. Even though, crop rotation and intercropping (in part with N fixing plants) is widespread in Zambia, I consider these as separate economic activities outside the scope of this model.[24] A 20% share of fallow agricultural land is assumed (Burke, Frossard, et al., 2016) (cf. initial liming in t_1, Section 3.8).

The data set of Burke, Jayne, and Black (2016) is adapted for this paper by dropping all observations with missing field size or soil characteristics (soil group and RSG[25]), retaining $6,330$ of initially $7,131$ observations. To update the yield function to the reference season, I maintain the constant, coefficients, and time invariant variables of the estimated function and update its time variant variables with averages from the literature for the reference season (mostly Namonje-Kapembwa, Black, and Jayne (2015) and CSO (2016)).[26]

To create a production function (Equation 7) from the yield function, the latter is scaled with a capacity variable representing area.

The production function considers two types of inputs: area (including capital and labor for its cultivation) and fertilizers.

Area is total area used for maize in the reference season, 1.33 mn ha (CSO, 2016). It is allocated to producers by their share of area in the sample of Burke, Jayne, and Black (2016).

The fertilizers in the model, which also represent nearly all fertilizer used by Zambian smallholders are: Compound D (NPK fertilizer applied as basal at planting time, with a 10-20-10 percentage mix of N, phosphate, and potassium) and urea (N fertilizer applied after planting as top dressing, with a 46-0-0 mix) (Burke, Frossard, et al., 2016).

An additional input is lime, which can shift the production function upwards. Liming requirements per producer show the necessary quantity of lime to rise into a higher pH group. They are based on pH change as quadratic functions of liming for each texture group. The functions are fitted through the respective discrete recommendations in Vossen (2016). The assumption of a quadratic relationship between liming rates and soil pH is based on diminishing returns of liming as stated and illustrated for present-day Zimbabwe in Grant (1970). It is further supported by a statistically significant quadratic effect of liming rates on soil pH for Brazilian oxisols (Fageria and Baligar, 2008).

4.3 Cost

Adding exogenous cost data (predominantly Burke, Hichaambwa, et al. (2011)) allows the

[23] High clay content of Solonetz (International Union of Soil Sciences Working Group WRB, 2015) also guarantees a certain robustness against acidifying N fertilizer.

[24] In Burke, Jayne, and Black (2016) only 0.8% of fields were used for N fixing crops in the preceding year and only 3.6% were intercropped with them in the current year. Also in the sample used in Namonje-Kapembwa, Black, and Jayne (2015) only 2.3% of fields are intercropped, but the authors mention intercropping was a common practice in Zambia. Other sources indicate high adoption rates of crop rotation in Zambia, cf. Manda et al. (2016) for Eastern Province (77% of their sample) and Mason, Jayne, and Mofya-Mukuka (2013) states 62% for 2010-11 and/or 2009-10 based on data from the 2012 Rural Agricultural Livelihood Survey (RALS).

[25] cf. International Union of Soil Sciences Working Group WRB (2015)

[26] Interaction terms are products of averages.

formulation of a cost function (Equation 8) for a profit maximization problem subject to exogenous output prices.

Transport costs vary by producer, based on average distances to the nearest district town in the sample of Burke, Jayne, and Black (2016), and distance to the nearest private fertilizer sales point (Chapoto and Jayne, 2011). For outputs, they also vary based on buyers (cf. Chapoto and Jayne (2011)). Transport of lime is considered to be between farms and the nearest district town.

There is no direct cost of land, because most Zambian farmers are granted free use of land by traditional local authorities (Burke, Hichaambwa, et al., 2011). Hence, modeled costs of area are rather costs for cultivating that area, exclusive of fertilizer and lime. They include costs of labor, animals, and machines, each hired and owned, and costs of seeds and pesticides (Burke, Hichaambwa, et al., 2011).[27] They amount to 216 USD/ha, based on Burke, Hichaambwa, et al. (2011).

Fertilizer prices at sales points of 578 USD/t for basal and 555 USD/t for top dressing are averages based on Thapa and Keyser (2012) weighted by provincial fertilizer use (CSO, 2016). Some fertilizer is subsidized, predominantly via the Farmer Input Support Programme (FISP) at 209 USD/t for each: basal and top dressing (Mason, Jayne, and Mofya-Mukuka, 2013).[28] The average price of lime at sales points is 20 USD/t, based on Mitchell (2005).

Producers' budgets set an upper limit to costs (Equation 11). They are based on the financial share (Davies, Lluberas, and Shorrocks, 2012) of median wealth per adult (>19 years old) in Zambia (Shorrocks, Davies, and Lluberas, 2010). This per adult wealth leads to average rural household wealth when multiplied with the rural population share of adults and average rural household size (CSO, 2012). Finally, multiplying the household wealth by total maize producers (CSO, 2016) and weighting this with the share of households per producer in the sample based on Burke, Jayne, and Black (2016) yields producers' budgets.

4.4 Trade and Taxes

Trade is modeled between Zambia and global commodities markets (Equation 2). In the status quo, Zambian maize exports generally stem from large scale farmers (Export.gov, 2017). These were projected to produce 0.233 mn t of maize in the reference season (Zambia Ministry of Agriculture, 2011). Exports in the reference season reach 0.358 mn t at an average free on board (f.o.b.) value of 379.35 USD/t (Figure 5), while imports at 305 t are negligible (United Nations Statistics Division, 2016).[29, 30]

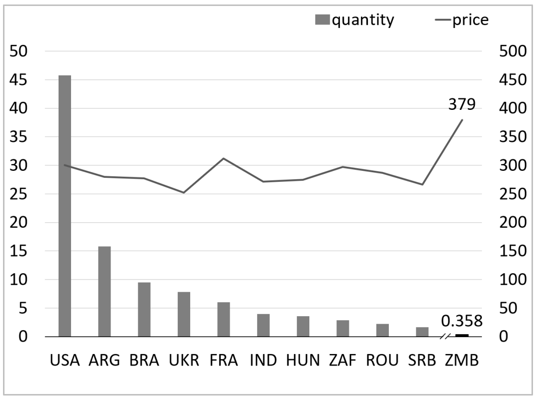

Figure 5: *Maize export quantities and average f.o.b. prices of top 10 exporters 2011 and Zambia, in mn t, 2011 USD/t*
data: United Nations Statistics Division (2016)

Due to the dominance of US exports (Figure 5)[31], global maize prices used for the counterfactual scenarios (Section 6.3) are based on the range of US Gulf f.o.b. export prices (Figure 6). They are modeled as constant over periods. Comparing them with prices of Zambian maize f.o.b. in the

[27] Costs for machines are subdivided into fuel and other cost using Conservation Farming Unit (2011) and Energy Regulation Board of Zambia (2017).

[28] I exclude subsidies of the Food Security Pack Programme (FSP), which may include 100 kg of lime in areas with acidic soils, due to the limited scope of the program (approx. 15,400 recipients in 2010-11) (Mason, Jayne, and Mofya-Mukuka, 2013).

[29] Food and Agriculture Oranization of the United Nations (2017) shows higher exports of 0.496 mn t at a nearly identical average value of 379.09 USD/t based on production forecasts from Zambia Ministry of Agriculture (2011).

[30] In the reference season, an export ban on maize bran was imposed (Sitko et al., 2017).

port of Dar es Salaam, decides whether exports are profitable. Transport is considered to be by truck rather than by train, because of the "poor state of rail infrastructure" in Zambia (Energy Regulation Board of Zambia, 2010). Export costs, including all transport costs and port charges, amount to 180 USD/t based on Teravaninthorn and Raballand (2009) and Tanzania Ports Authority (2012). Comparing global delivered duty paid (d.d.p.) prices in Lusaka with prices of Zambian maize, decides whether imports are profitable. Imports are assumed to enter from South Africa and import costs include all transport costs, amounting to 140 USD/t (Nkonde et al., 2011), and import duty. Maize incurs 15% import duty, but no export duty, excise tax, or VAT (Zambia Revenue Authority, 2014).

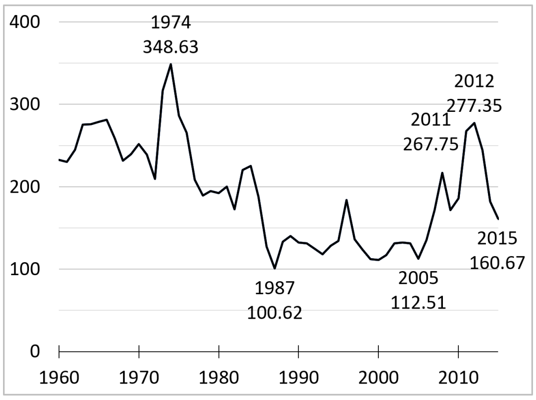

Figure 6: *global price of maize over time, based on annual US Gulf price f.o.b., in 2010 USD/t data: World Bank (2016a)*

5 Solution

The model is set up in three layers of mathematical problems: core problem (Section 5.1), intermediate problem (Section 5.2), and enclosing problem (Section 5.3).[32]

The core problem is the profit maximization of producers. It uses exogenous inputs for G, P, S, and T, where $g \in G$, $p \in P$, $s \in S$, and $t \in T$. Outputs are used to calculate WF.

The intermediate problem adds an equilibrium constraint to the core problem, endogenizing p. This is achieved via a binding local demand constraint (Equation 10). Solving this problem returns a subset of the solutions of the core problem, consisting of equilibria dependent on g, s, and t. In each step of its iterative solution approach, the core problem is solved.

The enclosing mixed-integer problem (MIP) describes the decision on discrete liming investment. For each s it solves the intermediate problem for all t and computes respective TWF. On this basis, the TWF optimal s is selected for all $g \in G$.

Subsequently (Section 5.4), the incentive compatibility of each s is tested by comparing each TPS_i associated with s with the respective TPS_i under liming investments of i that deviate from s. This is repeated for all $g \in G$.

At the prevailing real interest rate, model results of the first 20 periods matter for the analysis.[33]

5.1 Core Problem

The core problem is monotonic, since all constraints (Equations 3 to 7, 10 and 11) and the objective function (Equation 9) are monotonic. Because of the constraints, it is also bounded on a non-negative domain. In addition, Equations 3 to 6 and 10 are linear, Equation 7 is cubic and quasiconcave, and Equation 9 is bilinear. Therefore, the core problem is a non-convex, bounded, monotonic, cubicly constrained bilinear program (cf. Tuy (2000)). Also, the objective function (Equation 9) and the cubic production constraints (Equation 7) are multiplicative concave (cf. Konno and Kuno (1995)).[34]

Besides the optimal values for decision and objective variables, outputs of the core problem are CS and WF.

[32] The model is implemented in the Python programming language, version 3.6.3 (Rossum, 2017). Essential Python packages for the implementation are pandas 0.23.3 (McKinney et al., 2018), NumPy 1.14.5 (Oliphant, 2018), and Pyomo 5.5.0 (Hart et al., 2017).

[33] Present values of the last model period (t_{19}) are <2% of their future values.

[34] The core problem is solved using Ipopt, version 3.12.4 (Wächter and Biegler, 2006).

5.2 Intermediate Problem

The purpose of the intermediate problem is to find a hypothetical short term market equilibrium without trade, consisting of a price and the corresponding quantity. A binding local demand constraint (Equation 10) in the core problem characterizes the equilibrium. Whereas in the core problem, p is exogenous, in the intermediate problem, it is not. A bisection algorithm is applied to potential ps. In each iteration of the bisection the core problem is solved with a different p, decreasing the slack variable of the local demand constraint. To ensure isolation, g is continuously set equal to p. The resulting price gap of zero cannot exceed positive costs of trade. When the slack variable is close enough to zero, the constraint is considered binding and the algorithm stops. The instance of the core problem solved in the last bisection iteration returns the equilibrium.

To evaluate trade opportunities later on, the core problem can be solved with an independent g and p from the established hypothetical equilibrium in isolation.

5.3 Enclosing Problem

Each of the 648 viable permutations of producers' choices of pH groups is considered a liming scenario. Scenarios are ordered by area in higher pH groups, thus in $s = 0$ no one limes, while in $s = 647$ all producers lime enough to reach the high pH group (cf. Figure A1).

The MIP is solved by applying the intermediate problem to find the market equilibria of all s for all t and calculating respective TWF. Then, the TWF maximizing s is selected for all $g \in G$.

5.4 Incentive Compatibility

Since in the enclosing problem (Section 5.3) the TWF maximizing liming scenarios are selected and are not the immediate results of the profit maximization of producers, it is necessary to check whether these results are compatible with producers' incentives. Therefore, the incentive compatibility of each investment scenario is tested: For each i, regular TPS_i (all producers invest according to s) is compared to the respective TPS_i resulting from i deviating from s in his investment.

The deviation TPS_i is calculated by solving the core problem (Section 5.1) for all periods with i as only producer. In this calculation, to model i as atomistic price taker, p is maintained fixed at its values from the regular solution and the local demand constraint (Equation 10) is dropped. This is repeated for all possible deviations of i and all $s \in S$, selecting the maximum TPS_i for each s.

If lime investments at maximal TPS_i deviate from s, s is unstable and the scenario resulting from the deviation is tested. Repeating these steps, the model either converges to a stable investment scenario, i.e. an incentive compatible equilibrium (that can differ from the TWF optimum), or it oscillates between scenarios, i.e. it remains in a disequilibrium.

This is repeated for all $g \in G$.

6 Results

After an assessment of the goodness of fit of the model (Section 6.1), the model is used for a comparative analysis between a baseline (Section 6.2) and counterfactual scenarios (Section 6.3). The baseline considers neither trade nor liming, whereas the counterfactuals consider both. The goal is to quantify the WF effect of the government introducing knowledge about the benefits of liming into the market and potentially in a second step of it guaranteeing WF optimal investments in liming. Table A1 shows the absolute values of the model results. Section 6.4 presents sensitivity analyses on producers' budgets, fertilizer prices, transport costs of lime, and interest rates.

6.1 Goodness of Fit

I test the goodness of fit of the cumulative production function and of the entire model. To test the fit of the production function, I compare the sum of the outputs of all production functions without liming with the 2.718 mn t of maize produced by Zambian smallholders in the reference period (CSO, 2016). Parameters and decision variables (shares of available areas used and fertilizer rates) of the production functions are fixed at their averages for the reference period. This shows that the output of the cumulative production function at 2.651 mn t is only 2.45% below the reference value (Figure 7).

To assess the goodness of fit of the entire model, I solve the intermediate problem (Section 5.2), which contains various instances of the core problem (Section 5.1), without liming investments (scenario 0). Different from the testing of the production function, here, all decision variables are endogenous and prices matter. The resulting input and output quantities (Table A1, column: baseline) are compared with those of the reference year (Figure 7).

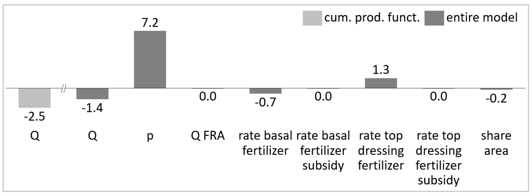

Figure 7: *Goodness of fit of production function and entire model via difference between model results and values of reference season, in percent of reference values*

The modeled market equilibrium is at a price of 203.12 USD/t and a produced quantity of 2.680 mn t. The baseline price exceeds the reference of 189.42 USD/t by 7.2%. Quantity falls short of the reference by 1.4%. No maize is exported at a global price of 268 USD/t (World Bank, 2016a). At the given costs of trade, the market will be isolated at global prices on the interval from the historical low of 100 USD/t up to 382 USD/t (Figure 6). In the reference season, exports exceeded projected production from large scale producers by 0.125 mn t at an average export value of 379.35 USD/t (Section 4.4). Most of this moderate export quantity went to neighboring Zimbabwe (United Nations Statistics Division, 2016) and for the purpose of this analysis, is not considered participation in the global maize market.

At a subsidized price of 263 USD/t[35], selling maize to the FRA is profitable even at high global prices. In all model runs (Table A1), the largest possible amount of 1.752 mn t is sold to the FRA, equaling the reference value.

Rates of subsidized fertilizers match the average rates of the reference year at 41 kg/ha. The overall rates of basal and top dressing fertilizer of 80 and 89 kg/ha respectively resemble the reference values of 80 and 87 kg/ha. Also, the preference for top dressing fertilizer is matched, reflecting the limited impact of phosphate fertilizer on acidic soils. The difference between subsidized and overall rates is bought at market prices. At 99.8%, practically all area is employed, where the reference value is 100%.

6.2 Baseline

In addition to the goodness of fit assessment, the baseline offers the following information: Due to the absence of liming in the baseline, producers' acidity levels remain constant over all periods and equal to those of the sample data. The sector-wide share of soils with high, medium, and low pH is 0.8%, 53.6%, and 45.6% respectively. Since additionally, the liquidity constraints are non-binding, all periods are equal.

With this input combination, producers reach an average yield for maize of 2.02 t/ha and an average PS per area of 105.25 USD/ha.

In each period, CS of 1,212.4 mn USD and PS of 139.6 mn USD add up to WF of 1,351.9 mn USD. Thus, TWF amounts to 6,984.9 mn USD. The TPS is 721.1 mn USD and cumulative present value of CS, i.e. total CS (TCS) is 6,263.7 mn USD. The low ratio of PS to WF stems from the elastic supply and relatively inelastic demand of the industry. This is plausible for a staple food like maize.

6.3 Counterfactuals

The counterfactual analysis shows that imports are unprofitable at any historical global price (Figure 6), i.e. ≥100 USD/t. It also shows that with optimized liming, exports become lucrative at around 340 USD/t, which is expensive in the historical context and above the average prices of large exporters in 2011 (Figure 5).

[35] 65,000 ZMK/50kg (Mason, Jayne, and Myers, 2015)

Below, I describe the counterfactual results for two trade cases: first, isolation caused by global prices assumed to be on the interval 100 to 340 USD/t and second, an export case with the global price assumed to be at the historical peak-price of 350 USD/t. The latter is of interest to show the impact of exports. Yet, it should be seen as an unlikely event, since historically, a price of 350 USD/t was an exception. Differences between outputs of the two cases single out the effect of trade at that price after liming is adopted.

In both trade cases, before liming takes effect in t_1, acidity levels are the same as in the baseline. With investment in liming, they rise and production functions improve from t_0 to t_1. In the export case it is TWF optimal to lime all soils, so from t_1 onwards, high pH soils make up 100.0% of the available area (optimal scenario: 647). In isolation (optimal scenario: 414), high pH soils make up 50.4% of the available area. Neither low pH clay loam, nor muck soils (no matter their initial acidity) are limed beyond a medium pH and account for the remaining 49.6% medium pH soils. Low pH soils exist in neither trade case. These pH changes are achieved by a total average liming rate in t_0 of 4.17 t/ha for the export case and of 1.51 t/ha in isolation.

For some producers, this investment exhausts budgets, which are replenished over time with cumulative profits. Without trade, budget constraints bind only in t_0 and t_1, thus all following periods are identical. In the export case, more is invested into liming and exports require higher levels of production inputs, so, budget constraints bind longer. Thus, this section focuses on the initial and the first and last future periods (t_0, t_1, and t_{19}).

The initial period differs as follows from the baseline:

Producers with binding budget constraints reduce inputs other than lime and thereby their outputs. In isolation, these producers' soils are medium pH clay loam soils. In the export case, additionally, producers with both low and medium pH muck soils are financially constrained. Other producers take advantage of their rivals' price increasing quantity reductions by expanding their own quantities via higher input application.

Due to these not fully compensated reduced quantities, total quantity declines compared to the baseline (isolation: -0.6% to 2.663 mn t, export case: -1.1% to 2.650 mn t). Also, due to diminishing returns of fertilizers experienced by the financially unconstrained producers, marginal costs and local prices rise (isolation: +3.1% to 209.45 USD/t, export case: +5.5% to 214.38 USD/t). Exports are not yet profitable.

Figure 8 illustrates relative changes in production inputs caused by liming. In t_0, average fertilizer rates decline slightly overall. Returns to land do not diminish, so the share of used area hardly changes in t_0.

In both trade cases, WF declines in t_0 due to liming investments that lower PS and higher prices that lower CS. In isolation WF is 1,300.9 (-3.8%), PS is 94.4 (-32.4%), and CS is 1,206.5 mn USD (-0.5%), whereas in the export case they are 1,211.4 (-10.4%), 9.3 (-93.3%), and 1,202.1 mn USD (-0.8%) respectively. This translates into profits per area of 71.15 USD/ha (-32.4%) in isolation and 7.01 USD/ha (-93.3%) in the export case.

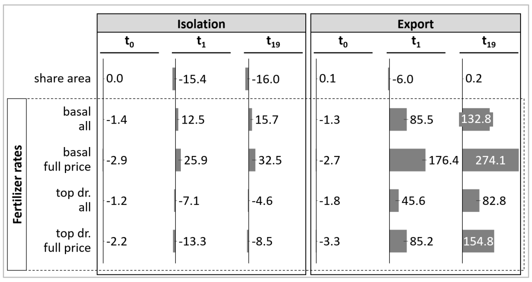

Figure 8: *changes in production inputs: optimal scenarios (414 in isolation and 647 at a global price of maize of 350 USD/t), in percent of baseline*

In both trade cases, binding budget constraints still hamper input application in t_1, but not in t_{19}, so over the future periods the following developments take place:

In isolation, total output reaches 2.795 mn t (+4.3%) in t_1 and 2.807 mn t (+4.7%) in t_{19}. Based on improved efficiency, this causes local equilibrium prices to drop by 20.8% to 160.94 USD/t in t_1 and by 22.8% to 156.72 USD/t in t_{19}.

Exports start in t_1 and increase as budget constraints loosen. They reach 1.348 mn t in

t_1 and 2.116 mn t in t_{19}. Total output climbs to 4.117 mn t (+53.6%) in t_1 and 4.885 mn t (+82.3%) in t_{19}. In the export case, the efficiency effect on prices is counteracted by the additional demand from abroad. With global prices at 350 USD/t, optimal liming still lowers prices by 16.1% to 170.50 USD/t starting with exports in t_1.

In isolation, these outputs are made possible by the following input combination (Figure 8): The used share of available area is 84.4% (-15.4%) in t_1 and 83.9% (-16.0%) in t_{19}. The basal fertilizer rate is 91 kg/ha (+12.5%) in t_1 and rises to 93 kg/ha (+15.7%) in t_{19}. This includes market purchases corresponding to 49 kg/ha (+25.9%) in t_1 and 52 kg/ha (+32.5%) in t_{19}. On the other hand, the top dressing rate declines to 83 kg/ha (-7.1%) in t_1 and ends at 85 kg/ha (-4.6%) in t_{19}. Therefore, top dressing rates at market prices amount to 41 kg/ha (-13.3%) and 44 kg/ha (-8.5%) respectively. In all periods, subsidized fertilizer rates reach their caps at 41 kg/ha each, which happens also in the export case. To maintain the elevated pH levels, reacidification from top dressing fertilizer is neutralized with liming at 0.73 t/ha in t_1 and at 0.29 t/ha in t_{19}.[36] Based on the used area, average yield is 2.49 t/ha (+23.3%) in t_1 and 2.52 t/ha (+24.6%) in t_{19}.

In the export case, 93.8% (-6.0%) of area is used in t_1 and at 100.0% (+0.2%) all of it in t_{19}. Basal fertilizer rates rise to 149 kg/ha (+85.5%) in t_1 and to 187 kg/ha (+132.8%) in t_{19}, showing market purchases of this fertilizer of 108 kg/ha (+176.4%) in t_1 and 146 kg/ha (+274.1%) in t_{19}. In contrast, top dressing fertilizer rates rise less steeply to 130 kg/ha (+45.6%) in t_1 and 163 kg/ha (+82.8%) in t_{19}. Thus, top dressing rates at market prices equal 88 kg/ha (+85.2%) and 121 kg/ha (+154.8%) respectively. Counteracting reacidification from top dressing fertilizer, 1.57 t/ha of lime are applied in t_1 and 0.58 t/ha in t_{19}. The sector reaches an average yield of 3.30 t/ha (+63.5%) in t_1 and 3.68 t/ha (+82.0%) in t_{19}.

In both trade cases, the change in fertilizer rates from a dominance of top dressing to one of basal fertilizer reflects that in deacidified soils phosphate is more available to plants. Furthermore, these numbers illustrate the sizable savings of resources in relation to output. These freed resources may be employed in the production of other goods or potentially in expanding production for exports as seen above. Regarding fertilizers in particular, the government could evaluate scaling back subsidies or fertilizer imports could decrease.

CS increases from liming but decreases with exports. In the final period, when adaptation to liming does not influence production anymore, CS reaches 1,258.4 mn USD (+3.8%) in isolation and 1,244.1 mn USD (+2.6%) with exports.

Like CS, PS per area and PS increase with pH, after a decline in t_0. In future periods in isolation, PS per area reaches 140.20 USD/ha (+33.2%) in t_1 and finally, 149.14 USD/ha (+41.7%) in t_{19}. This corresponds to PS of 157.3 mn USD (+12.7%) and 166.2 mn USD (+19.1%) respectively. With exports, PS per area grows to 158.87 USD/ha (+51.0%) in t_1 and then 184.25 USD/ha (+75.1%) in t_{19}, equivalent to PS of 198.0 mn USD (+41.8%) and 244.8 mn USD (+75.4%) respectively.

Not all producers increase their profits with widespread liming in the sector. In both trade cases, producers with already high pH soils experience a decline in profits due to the loss of their competitive advantage. In isolation this also holds for medium pH muck soils, which are not limed in this optimum.

Together, growing CS and PS lead to a surge in WF. In isolation, WF reaches 1,411.2 mn USD (+4.4%) in t_1 and 1,424.6 mn USD (+5.4%) in t_{19}. With exports, it amounts to 1,442.1 mn USD (+6.7%) in t_1 and 1,488.9 mn USD (+10.1%) in t_{19}.

Finally, cumulative present values of CS, PS, and WF allow a combined evaluation of investment costs and benefits spread over time (Figure 9). TWF is the objective variable of the enclosing problem (Section 5.3). Therefore, each counterfactual TWF necessarily at least equals that of the baseline. In isolation, with 7,225.7 mn USD it exceeds the baseline by 3.4% (WF effect). This increase is composed of growth in CS by 2.9% to 6,446.1 mn USD and of growth in PS by 8.1%

[36] Liming in t_1 includes initial liming of fallow fields, while all following liming exclusively maintains pH.

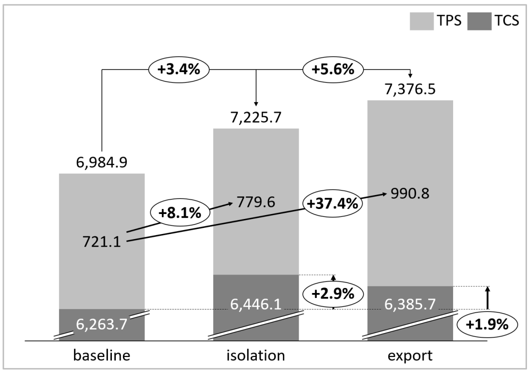

Figure 9: *model results: baseline (0 in isolation) and optimal scenarios (414 in isolation and 647 at a global price of maize of 350 USD/t), in mn USD*

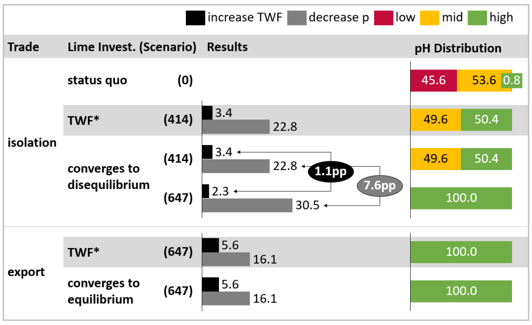

Figure 10: *Incentive compatibility of TWF optimal model results by trade case, in percent (of reference season or of total area for pH) and percentage points (pp)*

to 779.6 mn USD. In the export case, TWF of 7,376.5 mn USD exceeds the baseline by 5.6%. Here the rise is composed of CS augmented by 1.9% to 6,385.7 mn USD and PS augmented by 37.4% to 990.8 mn USD.

Even thought, the size of the WF effect may look small at 3.4% and 5.6% (isolation and export case respectively), price reductions from liming at 22.8% and 16.1% are remarkable. Low price elasticity of demand causes large CS and influences the size of the relative WF effect. This should not dwarf the perception of the absolute TWF increase at 240.9 mn USD and 391.6 mn USD or of the economically and politically highly significant price reductions.

As described in Section 5.4, I test all lime investment scenarios for their incentive compatibility. Test outcomes for the TWF optima of both trade cases are shown in Figure 10.

In the export case the TWF optimal scenario (647) is an equilibrium. In isolation, the TWF optimum (414) is not stable. Here, the model oscillates between the TWF optimal investment scenario and the scenario where all soils are limed into the high pH group (647). Optimally, 49.6% of soils would stay in the medium pH group. If the government lets producers lime these soils further, the TWF increase might fall by 1.1 percentage points to 2.3% compared to the optimal increase of 3.4%. At the same time the price decrease might be even more accentuated at 30.5%, surpassing the TWF optimal decrease of 22.8% by 7.6 percentage points. Without the second intervention (Section 3.13) the sector converges to and remains in a disequilibrium, where either of the two solutions may manifest.

6.4 Sensitivities

To check the robustness of the regular results (Section 6.3), I run sensitivity analyses on four parameters: budget for maize production, fertilizer prices, interest rate, and transport cost of lime. I solve the model with each parameter value independently reduced or increased compared to its regular value. The analyses show differences in resulting soil pH (Figure 11), in increases of TWF, and in decreases of final local prices (Figure 12).

The budget for maize is considered at 80%, 120%, and 1000% of the regular value. In contrast to the former two values, the latter renders the budget constraint irrelevant. A reduction to 50% of the regular budget would be render the model infeasible.

Fertilizer prices are altered to 50% and 150%, based on recent variation of the global prices of urea and phosphate rock (World Bank, 2016a).[37]

I consider interest rates at 80% and 120% of the regular value.

Transport costs of lime are altered to 90% and 300% of their regular values. In the counterfactuals, because of widespread demand, lime is produced in proximity to maize farmers and bought at the nearest district town. Resulting transport costs can be considered

[37] I consider prices after the spike of 2008.

low compared to empirically observed transport costs (Mitchell, 2005). Hence, I lower the parameter value only slightly on the lower end, but triple it on the upper end.

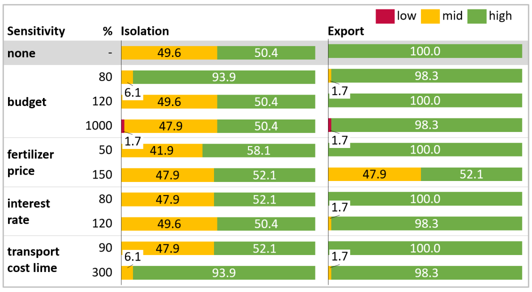

Figure 11: *sensitivity of acidity: optimal scenarios in isolation and at a global price of maize of 350 USD/t)*
in percent of total area

Regarding the distribution of soil acidity after TWF optimal liming (Figure 11), in isolation, regular results are mostly stable (49.6% in the medium and 50.4% of soils in the high pH group). Only the cases with reduced budgets and with increased transport costs of lime deviate markedly. Both cases show 93.9% of soils with high pH and the remainder with medium pH (initially low pH muck).

In the export case, it stands out that only increasing fertilizer prices changes the acidity distribution significantly, when 47.9% of soil (initially low pH clay loam and medium pH muck) remain in the medium pH group and the other 52.1% have high pH. Since these high fertilizer prices render exports unprofitable, the acidity distribution equals that in isolation. With all other alterations the high pH group includes nearly all (98.3%) or all soils, as in the regular case.

Independent of trade, it is noticeable that the only accounts of unlimed low pH soil appear when, due to a sizable initial budget, no liquidity constraint exists.

With respect to increases in TWF (Figure 12), in isolation, three parameters (budget in t_0, interest rates, and transport costs of lime) are negatively correlated with the respective increase in TWF. On the other hand, fertilizer prices are positively correlated with the increase in TWF. The largest negative deviation from the regular value (at 3.4%) happens without budget constraints or with low fertilizer prices (both at 2.9%). The largest positive deviation stems from high fertilizer prices (at 5.1%).

In the export case, the tendencies persist for interest rates and transport costs of lime, but changes in fertilizer prices stand out. Since increased fertilizer prices make exports unprofitable, the changes in TWF and p are the same as in isolation in this case. In contrast, low fertilizer prices allow exports even without liming. The largest positive deviation from the regular increase in TWF (at 5.6%) takes place at these low fertilizer prices (at 7.4%). The largest negative deviation (at 4.3%) happens without budget constraints or with increased costs of transport of lime.

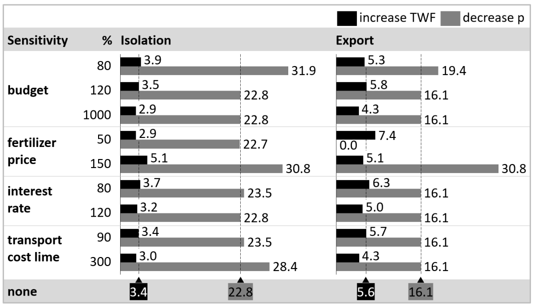

Figure 12: *sensitivity of increases in TWF and decreases in price in the final period: optimal scenarios in isolation and at a global price of maize of 350 USD/t)*
in percent of respective baseline

Evaluating decreases in p (Figure 12), the values of the isolation case are close to the regular outcome (at 22.8%) with three exceptions: low initial budgets, high fertilizer prices, and high transport costs for lime. All of these reduce supply and raise p in t_0 and then show larger reductions in p.

With exports most decreases in p are equal to the regular outcome (at 16.1%). Fertilizer prices cause the extreme exceptions: High fertilizer prices prevent exports and show the same decrease in p as the isolation case. Low fertilizer prices allow exports without liming, so global prices always determine the local price and no decrease in p exists.

In summary, results are sensitive to the tested parameters. Yet, they look robust, if trade decisions and budget constraints are not influenced too much.

7 Conclusion

This paper quantifies the WF effect of the counterfactual introduction of widespread agricultural liming on the Zambian smallholder maize market. Liming could raise pH levels of predominantly acidic farmland to more adequate levels for maize cultivation, improving fertilizer efficiency and consequently the efficiency of ISPs. Agricultural liming is well established in other regions.

The main finding is that at common world market prices, the market would be isolated from global trade and compared to the status quo, liming would optimally increase TWF by 3.4% accompanied by a local price reduction of 22.8%. Yet, the Zambian government might have to prevent liming that surpasses TWF optimal rates. In the case of global prices of 350 USD/t, the sector would export and its TWF would increase by 5.6% while the local price would drop by 16.1%. The size of the price and WF effects in both cases are economically significant. Considering the status of maize in Zambia, the results also carry great political weight.

Apart from the favorable price and WF effects, liming leads to a relative reduction of top dressing with N fertilizer. The need to counteract the acidifying effect of N to maintain elevated pH levels increases the cost of this fertilizer. On the other hand, application of basal fertilizer, a mix of N, phosphate, and potassium, increases in relative and absolute terms. Higher pH levels increase the availability of these nutrients to plants, improving the profitability of the fertilizer. This increased profitability of basal fertilizer further reduces the relative use of top dressing fertilizer. Given the local abundance of limestone, its application seems recommendable to increase the profitability of fertilizers. This could increase outputs, as shown in the model, or reduce costly imports of fertilizer while maintaining output levels.

In any case, the increased efficiency offers a way to make better use of scarce resources. This is welcome, especially in face of the debate on the limited availability of phosphate.

Widespread adoption of agricultural liming may not be beneficial to everyone. Producers with less acidic soils may lose their competitive advantage and suffer declining profits. Also, producers unable to afford up front expenses for liming their acidic soils would be at a competitive disadvantage. In this case, the government might facilitate financing or shift subsidies from fertilizers to lime. The FSP is an example of this, yet on a small scale in the reference season of 2010-11 (Mason, Jayne, and Mofya-Mukuka, 2013).

The focus of the analysis on the maize market, leaves repercussions on other markets open for further research. Expanding demand for lime would raise WF on its own market. On the other hand, WF on fertilizer markets may decrease if its consumption declined. Also, down the maize value chain, liming may cause changes that are out of the scope of this analysis: potentially lower prices of maize as input may impact WF on markets of maize derivatives.

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Appendices

A1. Absolute Values of Results

	unit	baseline	counterfactuals					
p global	USD/t	[100,382]	[100,340]			350		
scenario	-	0	414			647		
t	year	all	0	1	19	0	1	19
trade	-	isolation	isolation	isolation	isolation	isolation	export	export
TWF	mn USD	6,984.9	7,225.7	-	-	7,376.5	-	-
TCS	mn USD	6,263.7	6,446.1	-	-	6,385.7	-	-
TPS	mn USD	721.1	779.6	-	-	990.8	-	-
R lime	t/ha	0	1.51	0.73	0.29	4.17	1.57	0.58
Share pH hi	%	0.8	0.8	50.4	50.4	0.8	100.0	100.0
Share pH mi	%	53.6	53.6	49.6	49.6	53.6	0	0
Share pH lo	%	45.6	45.6	0	0	45.6	0	0
p EQ	USD/t	203.12	209.45	160.94	156.72	214.38	170.50	170.50
WF	mn USD	1,351.9	1,300.9	1,411.2	1,424.6	1,211.4	1,442.1	1,488.9
CS	mn USD	1,212.4	1,206.5	1,254.0	1,258.4	1,202.1	1,244.1	1,244.1
PS	mn USD	139.6	94.4	157.3	166.2	9.3	198.0	244.8
PS per Area	USD/ha	105.25	71.15	140.20	149.14	7.01	158.87	184.25
Yield	t/ha	2.02	2.01	2.49	2.52	2.00	3.30	3.68
QS	mn t	2.680	2.663	2.795	2.807	2.650	4.117	4.885
QS Z2Z	mn t	2.680	2.663	2.795	2.807	2.650	2.769	2.769
Q export	mn t	0	0	0	0	0	1.348	2.116
Q FRA	mn t	1.752	1.752	1.752	1.752	1.752	1.752	1.752
production inputs								
Utilization	%	73.9	58.7	61.6	61.9	51.3	79.8	94.7
Share area	%	99.8	99.8	84.4	83.9	99.9	93.8	100.0
R fbas	kg/ha	80	79	91	93	79	149	187
R fbas sub	kg/ha	41	41	41	41	41	41	41
R fbas fup	kg/ha	39	38	49	52	38	108	146
R ftop	kg/ha	89	88	83	85	88	130	163
R ftop sub	kg/ha	41	41	41	41	41	41	41
R ftop fup	kg/ha	48	47	41	44	46	88	121

Table A1: *model results by liming scenario: baseline (0 in isolation) and optimal scenarios (414 and 647 s.t. global price of maize)*

Utilization is defined for each s as the ratio between optimized output and technically maximal output, which is based on the upper bounds of fertilizers and land use.

A2. Liming Scenarios

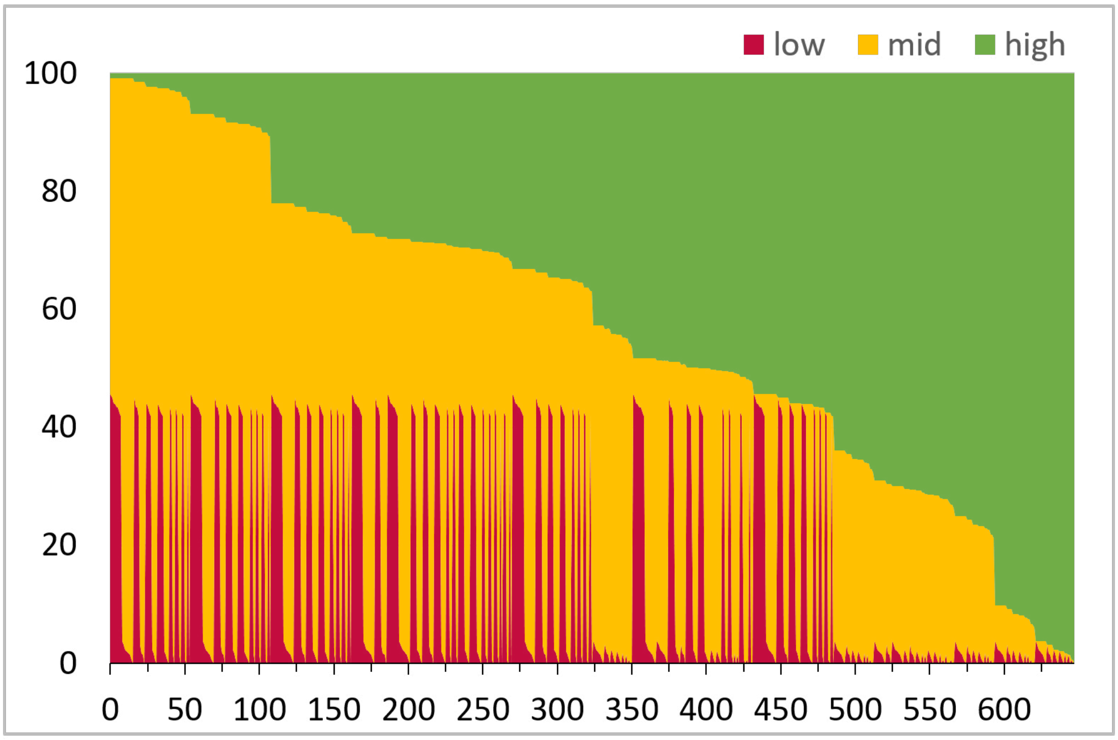

Figure A1: *all 648 liming scenarios ordered by share of area in higher pH groups, in percent of total area*