More Biofuel = More Food?

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Abstract

In face of increased efforts to mitigate climate change, biofuels may be included in reduction plans for greenhouse gas emissions. Feedstock for first generation biofuels and food crops both use arable land and may compete for it. Also, fuel is an input for the production and transport of food. The purpose of this paper is to quantify with empirical data how these two aspects affect market outcomes and to introduce a counterfactual setting where the latter aspect dominates the former. The setting allows an expansion of biofuel production to increase food production by lowering costs of production and transport. Namely, lower costs increase market access, allowing a higher utilization of idle production capacities for food crops. For this quantification, I develop an open market, welfare maximizing, partial equilibrium model for three interdependent goods fuel, fuel feedstock, and food (these goods are represented by diesel/biodiesel, palm oil, and cassava/maize respectively). The model is calibrated to Zambia, which exhibits the necessary underlying conditions of underutilized agricultural capacity, high transport costs, and low exports of food. Compared to a baseline, model results show the counterfactual switch from fossil diesel to biodiesel to reduce the diesel price by 51%. This increases food supply (cassava and maize combined) by 0.4% and decreases related prices by 3%. Overall welfare increases by 9.9%. If additionally, a higher world market price of maize renders exports just profitable, overall welfare continues to gain 9.9%, domestic food supply rises by 0.3%, and related prices drop by 2%, but food supply including exports grows by 32%. Furthermore, the introduction of a palm oil based biodiesel sector eliminates import dependency on fossil diesel and palm oil.

Keywords: Biofuel, Land Use, Energy Economics, Partial Equilibrium Model, Zambia
JEL Classification: C61, O13, O55, Q16, Q18

1 Introduction

In the mid-2000s, food prices rose distinctly, while biofuels became more popular. A relationship between the two trends is disputed, but the underlying fact that feedstock for first generation biofuels and food crops use land should be considered when contemplating large expansions of biofuel production.[1] While second and third generation biofuels aim to prevent the competition with food crops for land, future plans to avoid greenhouse gas emissions may also include first generation biofuels, thus the question about competition for land matters, at least in the medium term.

A second connection between food crops and fuel is that the latter is an input for the production and transport of the former. Thus, the price of fuel influences the costs of food crops and subsequently their supply. This connection is less prominent in the discussion on biofuels.

I explore the interaction of both aspects by introducing a setting where the second aspect is crucial. In fact, an expansion of cheap biofuel production can be beneficial to food supply, if high fuel prices cause high costs of production and of market access, secluding producers of underutilized agricultural areas from markets. Biofuel production would

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[1] Generally, the first generation of biofuels uses edible crops as feedstock, the second generation uses non-edible biomass, and the third generation is based on algae.

lower fuel costs and thus, transport and market access costs. Given favorable market conditions, producers would increase food output to profitably supply it to the market.

To scrutinize how different parameters affect the two aspects and the economic viability of the setting, I develop a static, spatial, welfare maximizing partial equilibrium model of the involved sectors (fuel, fuel feedstock, and food) with domestic markets and distant world markets. Different model scenarios show under which circumstances food production profits from biofuels. The model uses fuel as input and output and is similar to welfare maximizing partial equilibrium models with basic and refined goods. In those models, the production processes of refined goods use basic goods as inputs. An example for this type of model is the global forestry model of Kallio, Moiseyev, and Solberg (2004), based on the theory of spatial equilibria in competitive markets (Samuelson, 1952).

The specific setting, where biofuel production benefits food production, requires high fuel prices causing high costs of both, production and transport of food, underutilized agricultural capacity, and as a result, a low level of food supplied to markets.[2] I choose Zambia as an application of the modeled setting, because it meets all requirements. Due to good data availability I pick the agricultural season of 2010-2011 (based on maize) as reference period to measure the goodness of fit of the model.

The production and transport of crops predominantly uses diesel as fuel. Zambian diesel prices are high in comparison with other countries (World Bank, 2016b) and all diesel is imported (ERB, 2010). Because of Zambia's geography as a vast landlocked country, distances to domestic markets and international ports are long. Thus, diesel prices matter for transport costs. The biofuel substitute for fossil diesel is biodiesel, which is currently not produced in Zambia.[3]

Underutilized agricultural capacity exists, because maize, the most important Zambian staple food, has significant potential for yield improvements. Smallholders produce over 92% of maize output (CSO, 2016; Zambia Ministry of Agriculture, 2011), but they use less than the recommended amounts of fertilizer and suffer from acidic soils (Burke, Jayne, and Black, 2016). Hence, yields can be improved via increased use of fertilizers and soil acidity management (Hinkel, 2019). The analysis considers only maize production by smallholders.

Due to its warmer climate with more rainfall, Zambia's north[4], as opposed to the rest of the country, allows the production of cheap biodiesel based on palm oil (Haggblade and Nyembe, 2008; Sinkala, Timilsina, and Ekanayake, 2013).[5,6] Palm oil is the most efficient potential feedstock for Zambian biodiesel (Sinkala, Timilsina, and Ekanayake, 2013). In the reference season, it is not produced in a significant amount in Zambia and imported on a low level for non-fuel purposes (Sinkala, Timilsina, and Ekanayake, 2013; United Nations Statistics Division, 2016). Cassava, is the second most important staple food in Zambia, and lacks far behind maize in terms of national output, but in the north, it is more important than maize (Haggblade and Nyembe, 2008). Therefore, it is included in the analysis.

This paper assumes a fully developed market for biodiesel, where counterfactual infrastructure and production sites are in place and running in the modeled period. Thus, the effect of cheap biodiesel on the modeled sectors is not confounded by a multi-year ramp-up period for the establishment of production (e.g., initial growing of oil palms) and infrastructure. The lack of an adequate political and regulatory framework or additional constraints in the modeled value chains can change the results via additional costs, as Hartley et al. (2019) observes for a model

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[2] While the specific setting requires these conditions, the model itself can be flexibly used to analyze the modeled sectors without strict requirements on capacities, costs, or prices.

[3] By 2017, no commercial biodiesel production exists (Samboko, Subakanya, and Dlamini, 2017). Potential non-commercial production is not considered.

[4] As modeled, northern Zambia includes Luapula and Northern Province, which in the reference season, also include most of present-day Muchinga Province.

[5] Cf. Verheye (2010) for general information on the cultivation of oil palms.

[6] Zambia's first palm oil plantation is located in Mpika (Muchinga Province) in northern Zambia (Zambeef Products plc, 2015).

of a counterfactual export-oriented Zambian bioethanol industry. In mid-2019, the Zambian government communicated that it developed a blending ratio and pricing mechanism for biodiesel without giving further details (Sapp, 2019).[7]

Drabik, Gorter, and Timilsina (2016) analyses the production of biodiesel in Zambia based on soybeans, but does not consider the effects on transport costs. This paper extends Drabik, Gorter, and Timilsina (2016) by endogenizing fuel costs and by linking biodiesel production to food production and trade with the world market.

Model results indicate that local production of biodiesel reduces import dependency by eliminating pricey imports of fossil diesel and palm oil.

Compared to a baseline, using only biodiesel reduces the diesel price by 51%, which reduces transport and production costs and increases food supply (cassava and maize combined) by 0.4% while decreasing their price by 3%. Overall welfare expands by 9.9%. If additionally, export to the world market is just profitable, diesel prices fall by 49% and overall welfare still expands by 9.9%, since export profits are not big enough to markedly raise welfare. Domestic food supply increases by 0.3%, and the related price drops by 2%. Food supply including exports grows by 32%. This biodiesel based export case causes an expansion in the use of available land for food crops. Since these increases in production stem from technological progress rather than from net-expansion of agricultural area, welfare is assumed to rise with limited ecological impact.[8]

The focus of the analyses lies on overall welfare implications of different biodiesel scenarios and related changes in prices, quantities, and land use. Therefore, distributional issues or the organization of production, as well as potential implications on greenhouse gas emissions lie outside the scope of this paper.

The remainder of the text is organized as follows. Section 2 describes the model. Section 3 outlines the data. Section 4 analyses and discusses the model outcomes, including a sensitivity analysis and Section 5 concludes.

2 MODEL

I develop a static, deterministic, computable, and spatial partial equilibrium model.[9] It consists of the linked Zambian markets for cassava, crude palm oil, maize[10], and diesel.

All markets are assumed to generate welfare (WF) maximizing outcomes due to perfect competition or regulation. A high number of consumers and price-taking producers defines the markets of the homogeneous agricultural goods, guaranteeing perfect competition. The market for diesel is a regulated monopoly, assumed to produce a homogeneous good at marginal costs. In addition, the counterfactual production of biodiesel is assumed to be fragmented, adding a competitive fringe to the market for diesel. Information on prices and capacities is transparent and no entry or exit barriers exist. By assumption, production factors are mobile and no externalities exist. This perfectly competitive setting is implemented as a WF maximization over all markets. Matching supplies with demands, equilibria on the markets consist of sold quantities and market clearing prices for the respective goods.

This static model focuses on a single annual period, representing the annual production cycle of the dominant agricultural good, maize.[11] The model is evaluated at a point in time at the beginning of the annual growing cycle. All markets clear simultaneously during the period.[12]

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[7] Already in 2011, the government announced a 5% blending ratio for biodiesel to be reached by 2015 (Sinkala, Timilsina, and Ekanayake, 2013), but the ratio was never implemented (Samboko, Subakanya, and Dlamini, 2017).

[8] The model does not quantify ecological impact (e.g., effects on biodiversity or greenhouse gas emissions).

[9] The model is implemented in the Python programming language (Rossum, 2017). Used packages include Pyomo (Hart and Woodruff, 2017) and Pandas (McKinney et al., 2018). The model is solved with version 3.12.4 of the Ipopt solver (Wächter and Biegler, 2006).

[10] The market for maize is extensively based on Hinkel (2019).

[11] Other modeled goods are less cyclical.

[12] For maize, storage losses alone reach 7% in the private sector and up to 32% at government storage sites (Sitko and Kuteya, 2013). Thus, generally high storage costs (losses and other costs) and therefore no significant

Markets are generally open for trade (import and export) considering costs of trade, i.e. transport costs and trade charges. Restrictions to trade (quotas and tariffs) may be implemented (cf. Section 2.2). Neither re-import nor re-export are considered.

2.1 Goods

The partial equilibrium model focuses on a selection of goods, $g \in G = \{\text{biodiesel } (bid)$, cassava (cas), crude palm oil (cpo), diesel (dsl), fossil diesel (fod), maize $(mze)\}$.

In this model, diesel is a blend of biodiesel and fossil diesel, based on an exogenously regulated mixed in share of biodiesel ($\mu \in [0, 1]$, Equation 5). Biodiesel has a lower energy density than fossil diesel. Fuel demand is given in fossil diesel units and its energy content must be met by supply. Thus, at any given price, with growing μ, supplied quantity of blended fuel increasingly exceeds that of fossil diesel. Once energy content is internalized in such a way, consumers are assumed to consider all fuels equivalent.[13] By-products of biodiesel production are disregarded due to their low economic value.[14,15]

Both cassava and maize are starchy staple foods. The analyses assume perfect substitution and trade both goods on the same market.[16] While cassava is consumed in various forms (e.g. fresh roots), in the model, it is represented as dried chips, i.e. flour equivalent units, to guarantee comparability with maize (cf. Haggblade and Nyembe (2008)).[17] By-products of cassava (leaves and peel) are disregarded due to their low economic value as food or animal feed (Cadoni, 2010).

Crude palm oil is sold for conventional final consumption (mainly cooking). Based on the situation in neighboring Tanzania (3ADI+, 2019), it is assumed that by-products (e.g. kernel cake and palm trunks) have no commercial value in Zambia, so they are not considered. For this model, palm oil[18] is chosen as the feedstock for biodiesel, due to its high yield and subsequently low cost of production (Sinkala, Timilsina, and Ekanayake, 2013). Palm oil used for fuel is assumed to enter the biodiesel production process directly at the plantation and is not sold. This way, biodiesel production influences the market of palm oil by competing for suitable land, rather than by increasing demand for palm oil.

In general, interactions between markets are modeled fundamentally via the competition for production inputs (fuel and arable land). Besides this competition for inputs and the possibility of substitution between flour equivalent starchy foods and energy equivalent fuels, markets of different goods are assumed to be unrelated.

2.2 Government

Besides the mentioned regulation of the fuel market, modeled government interventions on markets include subsidized inputs and purchases, the levy and refunding of value added tax (VAT), tariffs, and export quotas. Only export quotas are manipulated in the analyses to influence scenario results. All other government actions are modeled as constant and exist only to resemble the underlying markets better.

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storage of goods between periods are assumed.

[13] Needs for extra tank volume seem negligible for biodiesel with 91% of the energy content of fossil diesel (Drabik, Gorter, and Timilsina, 2016). A higher solidifying temperature of biodiesel is another prominent difference to fossil diesel, but negligible in tropical climates (Cukalovic et al., 2013).

[14] Cf. Farm-Energy (2019): Producing ten units of biodiesel generates approx. one unit of crude glycerol. In Zambia, glycerol is assumed to lack a viable market. In the United States, it sells at only 2.5-5 cents/lbs, so export is not an option. It may be disposed of in various ways, incl. composting, burning, or as animal feed.

[15] The production of biofuels can generate income from clean development mechanisms (CDMs) (Sinkala, Timilsina, and Ekanayake, 2013). This is not modeled, but would increase the profitability of biodiesel.

[16] Varying ratios of cassava to maize consumption and prices can be observed in different regions of Zambia, labeled "maize belt", "dual staple zone", and "cassava belt", cf. (Haggblade and Nyembe, 2008). The modeled price setting market of starchy foods considers cassava sales distant from production, such that production and transport costs of cassava closely resemble those of maize. This is the case between the dual staple zone and the maize belt (Haggblade and Nyembe, 2008).

[17] Fresh and dried cassava (weight ratio 4 : 1) differ in water content. Fresh roots are more perishable and their weight increases transport costs. Producing households in Zambia consume about 92% of cassava on-site (Haggblade and Nyembe, 2008).

[18] This analysis exclusively considers crude palm oil opposed to refined palm oil, therefore, I drop the qualifier from here on.

Subsidized inputs of fertilizers lower production costs of agricultural goods. Subsidized purchases by the Food Reserve Agency of the Zambian Government (FRA) exist for maize and guarantee qualified farmers a premium above the market price. FRA purchases of maize are limited at the level of the reference period. They are resold to the market at competitive prices later in the season.

VAT with non-zero rates increase costs to consumers and lower WF on the affected market.[19] There is no VAT on exports. Sellers of goods with non-zero VAT rates and exporters may reclaim input VAT.[20]

Tariffs are charged on different imports and exports, increasing the costs of trade. Export quotas exist only in the counterfactual analyses, where indicated.

2.3 Supply

Each producer ($i \in I$) chooses to produce non-negative quantities ($q_{g,i,j}$) of goods ($g \in G$) for different buyers ($j \in J$). Quantities are capped by upper bounds $\bar{q}_{g,i,j}$ based on finite capacities and demand (e.g., maximum demand from government for subsidized maize). Quotas can further limit exports.

$$0 \leq q_{g,i,j} \leq \bar{q}_{g,i,j} \tag{1}$$

All producers face unit costs of production ($cp_{g,i,j}$) and transport ($ct_{g,i,j}$), each divided into fuel costs and non-fuel cost parameters ($cp^{nf}_{g,i,j}$, $ct^{nf}_{g,i,j}$). Fuel costs for goods other than fuels are the constant fuel requirements for production ($rp_{g,i}$) and transport ($rt_{g,i,j}$) multiplied with the endogenous market price for diesel (p_{dsl}). Fuel requirements and non-fuel costs are constant.

Fuel costs of the production and transport of fuels are modeled as "iceberg" costs (Samuelson, 1954), i.e. a quantity of fuel destined for sale shrinks by its fuel requirements for production and transport. Fuel quantities lost as iceberg costs must be produced, but by assumption, are not transported.[21]

The total cost of supply (C) is the sum of all costs from production and transport:

$$\begin{aligned} C = \sum_g \sum_i \sum_j q_{g,i,j} \cdot \Big(& cp^{nf}_{g,i,j} + ct^{nf}_{g,i,j} \\ & + gov_{g,i,j} \cdot p_{dsl}(Q^{SZ}_{dsl}) \\ & \cdot \left(rp_{g,i} + rt_{g,i,j} \right) \Big) \end{aligned} \tag{2}$$

p_{dsl} is a function of the endogenous supply to the domestic (Zambian) diesel market (Q^{SZ}_{dsl}). Both, p_{dsl} and Q^{SZ}_{dsl}, are determined simultaneously.

For a better representation of the underlying markets, if it corresponds to the situation in Zambia, costs are adjusted for VAT and tariffs within $cp^{nf}_{g,i,j}$ and $ct^{nf}_{g,i,j}$, as well as in a non-negative parameter of government intervention ($gov_{g,i,j}$).

Producers are subdivided into Zambian agricultural producers (i.e. soils, $s \in S$), an importer, and a fuel blender.

2.3.1 Agricultural Producers

Agricultural producers are based on a nationwide data set of Zambian smallholder maize farmers (Burke, Jayne, and Black, 2016) grouped to representative producers defined by circumstances of production (Hinkel, 2019).

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[19] The present analyses do not cover government actions funded by VAT from the modeled sectors, but increasing WF elsewhere.

[20] By assumption, producers do not export goods directly, but sell to an exporter who pays market prices and reclaims all input VAT (on the market price and on the cost of transport). This market structure is in line with the pre-2010 illustration in Sitko and Kuteya (2013). Selling to exporters at market price, producers are assumed not to profit from the exempt rate on exports and can only reclaim input VAT if their sales already have non-zero VAT rates.

[21] This paper considers the quantity of output lost in production and transport as first degree iceberg costs of production and transport respectively. Second degree iceberg costs describe the amount of output lost in the respective production and transport of first degree iceberg costs. Higher degree iceberg costs follow the same pattern. This paper neglects higher degree (>1) iceberg costs, since their size would be relatively small and diminishing with increasing degrees. First degree iceberg costs of transport are consumed during the journey of a payload from producers to consumers, further decreasing the importance of higher degree iceberg costs of transport. Thus, first degree iceberg costs of transport cause first degree iceberg costs of production but no higher degree iceberg costs of transport, i.e. they are produced but not transported.

Building on Hinkel (2019), the counterfactual analyses assume that all producers lime their soils to sustainably raise pH levels to the optimal range for maize cultivation. This guarantees high efficiency in maize production and shows Zambian agricultural potential to produce additional outputs.

Agricultural producers differ based on their soil properties, their geography, and their remoteness. Soil properties, such as soil types (e.g. sandy soils) and typical tilling techniques, influence maize yields (Hinkel, 2019). Geographical location in northern Zambia, as opposed to the rest of Zambia, allows the cultivation of oil palms. Remoteness describes the average distances to sales points of agricultural inputs and outputs (Hinkel, 2019) and influences costs and fuel requirements of transport.

An additional representative northern producer group stands for farmers cultivating cassava, the dominant food crop of northern Zambia. Due to their location, they can grow oil palms. Based on their past preference for cassava over maize, by assumption, they cannot grow maize.

The ability to cultivate oil palms enables northern producers to supply crude palm oil and/or biodiesel based on palm oil.

Goods of agricultural origin (biodiesel, cassava, palm oil, and maize) compete for a common input, the exogenously limited arable area of agricultural producer s (A_s). In itself, arable land is not likely to be the capacity limit in Zambian agriculture, but it serves as a proxy for labor and capital restrictions on production (Hinkel, 2019) and generates the capacity constraints:

$$A_s \geq \sum_g \sum_j \frac{q_{g,s,j}}{yield_{g,s}} \tag{3}$$

$yield_{g,s}$ is defined as the constant average output of g, which producer s receives by applying a unit of arable land.

In addition to capacity constraints, sales to all markets are capped at respective saturation quantities.[22]

2.3.2 Importer

The importer can supply crude palm oil and fossil diesel from the world market.[23] World market prices of imported goods resemble constant production costs. Constant transport costs abroad include tariffs. Neither of these costs is divided into non-fuel and fuel costs, since there is no relation to Zambian diesel prices. Transport costs in Zambia are treated like those of domestically produced goods. Imports are limited to the saturation quantities of Zambian markets.

2.3.3 Fuel blender

A single fuel blender produces diesel as a blend of fossil diesel and biodiesel. Thus, it is not only a producer of diesel, but also a buyer of biodiesel and fossil diesel. Since the fuel market is strictly regulated, it is assumed that consumers can only buy fuel from the single blender, who sells at cost. Blending is bound by an input-output constraint, which states that diesel sales from the single blender to all buyers (j) must not exceed the sum of the blender's inputs (biodiesel and fossil diesel) from all its suppliers (i):

$$\begin{aligned} &\sum_j q_{dsl,blender,j} \leq \\ &\sum_i q_{fod,i,blender} + q_{bid,i,blender} \end{aligned} \tag{4}$$

The regulator exogenously predetermines the fuel blender's constant input ratio, μ:

$$\mu = \frac{\sum_i q_{bid,i,blender}}{\sum_i q_{fod,i,blender} + q_{bid,i,blender}} \tag{5}$$

Reformulating it creates the input constraint:

$$\begin{aligned} &\sum_i q_{fod,i,blender} \cdot \mu = \\ &\sum_i q_{bid,i,blender} \cdot (1 - \mu) \end{aligned} \tag{6}$$

All costs of blending and subsequent delivery to fuel markets are modeled as contained

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[22] The saturation quantity is defined at the intersection of the market demand function with the quantity axis, i.e. where the quantity is so large that the price is zero.

[23] Other imports (biodiesel, cassava, and maize) are historically irrelevant (United Nations Statistics Division, 2016) and therefore expected to have no effect on the analyses.

in the costs of the two inputs. Diesel sales to the Zambian market are capped at its saturation quantity.

2.4 Demand

All market demand ($Q^D_{g,j}$) stems from the different representative buyers and is divided into input demand for fuels and final consumption of all goods.[24]

2.4.1 Input Demand

Fuel requirements from the production and transport of non-fuel goods multiplied with the quantities of these goods (Section 2.3) create input demand for fuel. This demand is attributed to two representative buyers: demand from crop production (*dprd*) and demand from crop transport (*dtrn*). Input demand reduces free production capacity. It is always met, generating the constraints:

$$\begin{gathered} Q^D_{fod,j} \leq q_{dsl,i,j} \cdot \eta_{dsl} \\ s.t.\ j \in \{dprd, dtrn\},\ i = blender \end{gathered} \tag{7}$$

η_{dsl} is the constant ratio of energy content of diesel compared to fossil diesel. It adjusts with exogenous changes to μ.

2.4.2 Final Consumption

Potential final consumers form a sub-set of J which includes an exporter who sells to the world market, on-farm consumers of cassava and maize, and private buyers geographically distant from agricultural producers. Since reference prices are based on sales to the latter, these sales are understood to form the price setting markets and other domestic markets follow them.

The FRA (Section 2.2) is rather an intermediary than a final consumer, yet it adds WF to the partial equilibrium model. The government agency is modeled to buy maize at a fixed premium above the market price up to a limit based on its purchased quantity in the reference season. Later in the season, FRA purchases are resold to private buyers at market rates and therefore maintain the supply to the domestic market. Whereas sales to the FRA create production and transport costs, sourcing and marketing costs of the FRA are outside of the model. Thus, the per unit net-impact of the subsidy on WF is the sum of the premium and the difference of transport costs from the producer to private markets versus to the FRA.

Exports decrease the supply to domestic markets. Compared to world markets, Zambian markets have *small country* properties, i.e. trade with Zambia does not influence world market prices and demand functions on world markets (Q^{Dw}_g) are defined as:

$$Q^{Dw}_g = \begin{cases} \infty & if \quad p^w_g - ct_{g,j}(p_{dsl}) > p_{g,j'} \\ 0 & if \quad p^w_g - ct_{g,j}(p_{dsl}) \leq p_{g,j'} \end{cases} \tag{8}$$

$$s.t.\ j = export,\ j' = private\ buyers$$

Q^{Dw}_g depends on domestic market prices ($p_{g,j'}$), prices on the world market (p^w_g), and costs of the exporter ($ct_{g,j}$), which depend on domestic fuel prices just like other transport costs do.

On-farm consumption of cassava and maize is possible for every agricultural producer, s.[25] This consumption counts as supplied to the domestic market. On-farm prices can be deducted from the general market price by subtracting transport costs.

Apart form the exceptions (FRA subsidies, input demand, exports), modeled domestic (Zambian) demand quantities ($Q^{DZ}_{g,j}$) based on off-farm private buyers and on-farm consumption, are linearly dependent on market prices ($p_{g,j}$). Thus, the inverse demand functions are:

$$p_{g,j} = p^{ref}_{g,j} \cdot \left(\left(\frac{Q^{SZ}_{g,j}}{Q^{ref}_{g,j}} - 1 \right) \cdot \frac{1}{\varepsilon_g} + 1 \right) \tag{9}$$

$$s.t.\ j = private\ buyers + on\text{-}farm\ consumers$$

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[24] Final consumption is defined broadly, as perceived by the sectors in the partial equilibrium model.

[25] Palm oil is assumed to be produced on plantations without direct consumption (cf. 3ADI+ (2019), Zambeef Products plc (2015)).

Here, the own price elasticities of demand (ε_g) determine the slopes, while the reference equilibria (equilibrium quantities of the reference season ($Q^{ref}_{g,j}$) and equilibrium prices of the reference season ($p^{ref}_{g,j}$)) position the functions. $Q^{SZ}_{g,j}$ contains admissible on-farm consumption and sales to private buyers by producers, importers, fuel blenders, and the FRA. Reference quantities are defined in the same way.

On the price-setting fuel market, demand stems from not further specified domestic fuel use excluding input demand of the modeled sectors (Section 2.4.1). Input demand reduces the supply available to meet final demand for fuel. The export of fuel is assumed to be undesirable and not allowed in the model. Quantities trade on the fuel market in energy equivalent units of fossil diesel.

2.5 Welfare

Total WF summed over all markets is the objective variable to be maximized by the model. It comprises all surpluses of domestic producers and consumers, while disregarding government surpluses or deficits and surpluses abroad (i.e. from the consumption of exports and from sales to the Zambian importer).

WF is defined as the difference of the integrals under each price function and total costs over all markets at the equilibrium quantities ($Q^*_{g,j}$) (cf. Kallio, Moiseyev, and Solberg (2004)):

$$\max_{q_{g,i,j}} WF = \sum_g \sum_j \int_0^{Q^*_{g,j}} p_{g,j}(Q_{g,j})\, dQ_{g,j} - C \tag{10}$$
$$s.t.\ Q_{g,j} = \sum_i q_{g,i,j}$$

A further unconstrained WF maximization would exploit market links to the extend where market equilibria deviate from competitive outcomes.[26] To prevent such model behavior, an explicit profitability constraint for the domestic diesel market is necessary (Equation 11).[27] Costs of producing and transporting fuel via the blender to the market (including iceberg costs) must not exceed the blender's revenue on the diesel market ($dslm$). The revenue stems from selling quantities of diesel adjusted by their energy content ($\eta_{g'}$) to meet fossil diesel energy equivalence:

$$\sum_g \sum_i (cp_{g,i,j} + ct_{g,i,j}) \cdot q_{g,i,j} \leq p_{g',j'} \cdot q_{g',i',j'} \cdot \eta_{g'} \tag{11}$$
$$s.t.\ g \in \{bid, fod\},\ j = i' = blender,\ g' = dsl,\ j' = dslm$$

3 DATA

The model uses data from a range of sources, building on the data set of Hinkel (2019) and extending it especially with data on biodiesel, cassava, and palm oil. This section gives an overview of the type of data used and presents the main sources of data, while all sources are listed in the data appendix.

The time frame of the model is the Zambian 2010-11 maize season. All values are evaluated at the beginning of that season, i.e. October 2010. If necessary, any monetary value is inflated, deflated, and converted into US dollars of this point in time. To be able to compare all monetary values resulting from the model, sub-seasonal prices and costs are discounted to October 2010 using real interest rates. Distributions of sales and costs over the months of the season are approximated by a uniform distribution (for fuel and palm oil), maize planting and harvesting cycles (Hinkel, 2019), and cassava sales of prior years (Haggblade and Nyembe, 2008).[28]

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[26] Exploiting market links of the diesel market would manifest in unprofitable sales lowering the price of diesel. This would cause both, decreasing WF on the diesel market and lower fuel input costs on all other markets, leading to a net-increase in overall WF.

[27] This constraint is binding, since the optimization of the linked markets tries to exploit the fuel sector for the benefit of overall welfare. The shadow price of this constraint indicates the WF gain from a potential fuel subsidy, which is not considered here.

[28] Cf. Hinkel (2019), exchange rates are based on Bank of Zambia (2015), US inflation on Organisation for Economic Co-operation and Development (OECD) (2017), Zambian inflation on World Bank (2016b), nominal interest rates for Zambian smallholders on Haggblade, Kabwe, and Plerhoples (2011), and those for a counterfactual

3.1 Reference Equilibria

For the reference season in Zambia, an equilibrium on the maize and cassava market is considered at a quantity of 2.718 mn t of maize (CSO, 2016) and 0.503 mn t flour equivalent cassava at a price of 189 USD/t. Cassava production in the model stands for that of northern Zambia, where competition with palm oil is possible. This region represents 73% of area planted with cassava nationally and similar shares of households selling cassava (CSO, 2016). Cassava quantities are based on sales data (CSO, 2016) and an estimated sales to production ratio (Haggblade and Nyembe, 2008). The price is a national season average of population weighted monthly provincial maize prices (Hinkel, 2019). The modeled market does not trade significant amounts of maize (Hinkel, 2019) or cassava with the world market (United Nations Statistics Division, 2016). The assumed own price elasticity of demand for cassava and maize is -0.19.[29]

In the reference season, Zambia produces and exports no palm oil, such that consumption equals imports of 0.026 mn t at an average unit value of 1,228 USD/t (United Nations Statistics Division, 2016). Adding tariffs and domestic transport, the estimated equilibrium price is 1,374 USD/t. Palm oil is assumed to be imported via the port of Dar-es-Salaam from the leading global exporter, Malaysia (World Bank, 2016a). The assumed price elasticity of palm oil is -0.38 (FAPRI, 2017).[30]

The reference equilibrium on the diesel market includes no biodiesel, but an estimated 639.9 mn l fossil diesel, sold for an average seasonal price of 1.58 USD/l (ERB, 2017). For the equilibrium quantity, iceberg costs of fuel distribution and estimated input fuel demand for the other modeled sectors are subtracted from 651.1 mn l of fossil diesel (ERB, 2015b)[31] imported from Tanzania via the TAZAMA pipeline (ERB, 2010). The assumed price elasticity of demand of fossil diesel is -0.13 (Dahl, 2012).

3.2 Production and Transport

Producers of agricultural goods, ($s \in S$, Table 1) are defined by their circumstances of production (choice of arable goods based on local climatic conditions, soil type, and distance to markets). Each s is representative for a group of atomistic individual producers of the same circumstances of production.[32]

soil	area share	arable goods
nor cassava	18.5	bid, cas, cpo
nor clay loam	6.3	bid, cpo, mze
nor loamy sand	0.6	bid, cpo, mze
nor muck	1.1	bid, cpo, mze
roz clay loam	49.3	mze
roz loamy sand	17.9	mze
roz muck	5.2	mze
roz sandy loam	0.5	mze
roz Solonetz	0.7	mze

Table 1: *agricultural producers: share of arable area and potential production of that area, in percent*
data: based on Hinkel (2019), Burke, Jayne, and Black (2016), CSO (2016)

Producers are uniquely identified by their location and soil type (if relevant). The label "*nor*" indicates location in the warmer, higher rainfall north of Zambia (Haggblade and Nyembe, 2008), which enables the cultivation of oil palms for palm oil or biodiesel. Producers in the rest of Zambia (*roz*) lack these climatic conditions. The producer *nor cassava* represents all modeled cassava cultivation (see Section 3.1). Other producers can grow maize instead of cassava. These are distributed over soil types based on the data-set of maize cultivating Zambian smallhold-

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Zambian palm oil and biodiesel sector on Sinkala, Timilsina, and Ekanayake (2013).

[29] Cf. Hinkel (2019) for maize, based on FAPRI (2017). This is in the range of elasticities for maize in Dorosh, Dradri, and Haggblade (2009), which also estimates a Zambian own price elasticity for cassava of -0.2.

[30] For every available country including developing countries Malaysia, Indonesia, and India, which by assumption have a comparable elasticity as Zambia.

[31] This includes all gas oil and low sulphur gas oil sales except exports (irrelevant and minuscule in size) and sales between oil marketing companies (OMCs) to prevent double counting.

[32] During the evaluation of the goodness of fit of the model (Section 4.1), some producers from Table 1 are further split along their initial soil acidity levels (low, medium, or high). This distinction disappears after the assumed treatment of soils in the counterfactuals.

ers from Burke, Jayne, and Black (2016) (cf. Hinkel (2019)). Total cultivated area in the reference season is 1.63 mn ha, divided among producers as shown in Table 1.

Constant yields of maize differ with soil types and can be improved exogenously via soil acidity management with agricultural lime (Burke, Jayne, and Black, 2016; Hinkel, 2019) and fertilizer rates at recommended levels (Mason and Myers, 2013). Outside a goodness of fit evaluation (Section 4.1), the analyses always consider these improvements, generating individual, elevated yields between 3.56 t/ha and 4.25 t/ha. Constant yields of cassava[33] at 1.78 t/ha and palm oil[34] at 3.67 t/ha are modeled as unrelated to soil types. Palm oil is processed into biodiesel at a fixed rate (Whistance and Thompson, 2014), creating an overall biodiesel yield of 3,981 l/ha.

Production cost of maize is based on Burke, Hichaambwa, et al. (2011) and Hinkel (2019), that of cassava production on Cadoni (2010), and costs of palm oil and biodiesel production stem from Sinkala, Timilsina, and Ekanayake (2013). Cost shares of included transport and other fuel costs stem from the same sources and in the case of palm oil from Basiron (2005). Dividing fuel costs by fuel prices (ERB, 2017) yields fuel requirements of production.

Transport over land is considered to be by truck rather than by train, since the poor state of train infrastructure inhibits the use of this potentially cheaper transport option (ERB, 2010). Agricultural producers' remoteness is based on distances to district towns and markets in the aforementioned data-set from Burke, Jayne, and Black (2016) and Chapoto and Jayne (2011) respectively (cf. Hinkel (2019)). It is the ratio of a producer's average distance to towns and markets over the overall average distance. Transport costs included in production costs are weighted by remoteness and split into non-fuel and fuel cost using typical fuel shares of regional transport costs in southern Africa (Teravaninthorn and Raballand, 2009). Dividing these fuel costs by fuel prices (ERB, 2017) yields fuel requirements of transport.

Delivered duty paid (d.d.p.) import prices (United Nations Statistics Division, 2016; ERB, 2015a) include production, transport, and duties and their inner-Zambian shares of transport costs are split into non-fuel cost and fuel requirements like the costs of domestic goods.

3.3 Government

In the reference period in Zambia, three VAT rates exist: standard, zero rated, and exempt.[35] Standard rates apply to fuels, palm oil, and transport services, are levied at 16%, and qualify for input VAT refunds. Zero rated goods (including all exports) and exempt goods (including cassava, maize, and many farming inputs) attract no VAT. While zero rated goods qualify for input VAT refunds, exempt goods do not. All consumer costs and therefore prices include respective VAT. Input VAT on fuel inputs and transport services are refunded, where admissible.

Maize is the only modeled good benefiting from subsidized government purchases. In the reference season, these amount to 1.752 mn t, bought at a premium above the market price. The constant premium is defined as the difference between the fixed subsidized price of 263 USD/t[36] and the market price, both in the reference period.

Maize exports are not explicitly banned in the reference season (Sitko, Chamberlin, et al., 2017), but implicit hurdles exist, such as limited issuance of export licenses (Mason and Myers, 2013) and availability of export permits only in the capital, Lusaka (Nkonde et al., 2011). While no export tariffs are levied on the modeled goods, import tariffs exist for maize (15%) and for cassava and fuels (25%). Additionally, 15% excise duty is levied

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[33] Cassava yield is an average yield of surveyed districts weighted by the number of cassava growing households per district and excluding extreme values (Cadoni, 2010).

[34] Palm oil yield combines fresh fruit bunch yield (Sinkala, Timilsina, and Ekanayake, 2013) with an oil extraction rate (Verheye, 2010). It includes palm kernel oil and is comparable to expected yields at the first Zambian palm oil plantation (Zambeef Products plc, 2015). Modeled oil palms are assumed to be hybrids of the high yielding tenera variety and the Kigoma dura variety, which is adapted to regional growing conditions in neighboring Tanzania (3ADI+, 2019).

[35] For information on VAT and tariffs cf. Zambia Revenue Authority (2014), Zambia Revenue Authority (2020).

[36] Cf. Mason, Jayne, and Myers (2015) and Hinkel (2019).

on fossil diesel. I model only explicit trade barriers.

4 Results

Following an evaluation of the goodness of fit of the model (Section 4.1), I establish a baseline for the counterfactual analyses (Section 4.2). In a static comparative analysis, the solutions of various model scenarios are checked against this baseline (Section 4.3). Finally, a sensitivity analysis shows the effect of increasing biodiesel use in one of the counterfactual scenarios (Section 4.4).

4.1 Goodness of Fit

Based on the assumption of perfectly competitive or regulated markets in the reference season (Section 2), the goodness of fit of the model is evaluated by comparing the market equilibria resulting from the *WF* maximization in the status quo scenario (*STATUS QUO*) with the reference market equilibria from the literature. It is important to note, that monetary values from the literature as shown undiscounted in Section 3.1 are discounted to the beginning of the maize season to be used in the model and these discounted values are compared with the equally discounted model results.

STATUS QUO models the situation in the reference season by considering observed agricultural productivity in the cultivation of maize[37] and by not dedicating land to oil palms, neither for palm oil nor for biodiesel. Hence, all diesel is imported fossil diesel and all palm oil is imported, too.

The optimized equilibrium quantity on the diesel market is 640.6 mn l at a price of 1.52 USD/l. Quantities differ from the reference by -0.1%, leading to a deviation of 0.5% from the reference price (Figure 1).

The equilibrium quantities on the market for starchy foods are 2.642 mn t of maize and 0.537 mn t of cassava, selling for 170 USD/t. Thus, quantities deviate from the reference by -2.8% and 6.8% respectively, which balances to a deviation of -1.3% for the combined equilibrium quantity. The resulting difference in price is 6.7%. The model matches the maximum amount of subsidized maize purchases of 1.752 mn t, equaling the amount in the reference season.

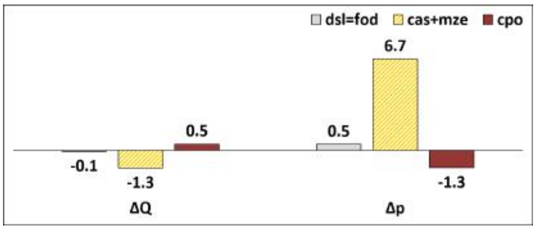

Figure 1: *Difference between model outputs and respective reference values, in percent of reference value*

In the model, 0.026 mn t of palm oil are consumed for 1,302 USD/t, which differs from the reference by 0.5% and -1.3% respectively.

Like in the reference, there are no exports to the world market.

The amplitudes of price differences exceed those of quantity differences due to relatively inelastic demand functions, which are typical for basic goods such as fuel and staple foods.

Overall the model uses 100% of the arable land used in the reference season. Therefore, the areas dedicated to the two available crops, cassava 19% and maize 81%, equal the areas of the producers able to cultivate these crops (Figure 2).

4.2 Counterfactual Baseline

The *STATUS QUO* aims to match the situation in the reference season as close as possible and is used to assess how well the model is calibrated. Its use as benchmark against the counterfactual scenarios is limited, because the effects of too many changes would overlap. The counterfactual baseline (*CF BASE*) serves this purpose better, because different from *STATUS QUO* and like all counterfactuals, it considers effective yield improvements for maize via liming and recommended fertilizer rates. Apart from this, it is equal to *STATUS QUO* in its inputs. The exogenous one-time improvement of all individual maize yields relaxes the capacity constraints on land suitable for maize production (Equation 3) and lowers unit costs (Equation 2).

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[37] This includes observed, lower than recommended fertilizer use and untreated soil acidity.

scenario	improved yield mze	μ (percent)	p^w_{mze} (USD)	domestic cpo production	export ban cpo
STATUS QUO	no	0%	224	no	n/a
CF BASE	yes	0%	224	no	n/a
CF ISOB	yes	100%	224	yes	yes
CF EXPO cpo	yes	100%	224	yes	no
CF ISOF	yes	0%	278	yes	yes
CF EXPO mze	yes	100%	278	yes	yes

Table 2: *scenario definition: status-quo and counterfactuals*

The baseline generates an equilibrium on the diesel market with 639.4 mn l of fossil diesel, marketed at 1.53 USD/l. On the market for starchy foods, the equilibrium quantity is 3.373 mn t combining 2.905 mn t of maize and 0.468 mn t of cassava, showing the shift in competitiveness of the two crops after the improvement of maize yields. The related price is 119 USD/t. Imports of palm oil continue to supply the entire market of 0.026 mn t for 1,302 USD/t.

4.3 Counterfactual Scenarios

Different values for a range of model inputs define the scenarios (Table 2). These inputs are: use of improved maize yields, biodiesel share (μ), the maize price on the world market (p^w_{mze}), possibility of domestic palm oil production, and application of an export ban on palm oil.

Different from *CF BASE*, all following counterfactual scenarios consider the domestic production of palm oil for import substitution.

The main counterfactual scenario, *CF ISOB*, still shows isolated (*ISO*) markets without trade, even though it is 100% biodiesel-based (*B*). Its share of biodiesel is varied in a sensitivity analysis (Section 4.4).

CF EXPO cpo extends *CF ISOB* by allowing exports of palm oil, which are prevented in other scenarios via export quotas at 0 t.

CF ISOF differs from *CF ISOB* by using only fossil diesel (*F*) and by considering an elevated p^w_{mze}, regardless of which, isolation from trade persists (*ISO*).

CF EXPO mze varies from *CF ISOF* by considering μ at 100%, instead of at 0%. Given the high p^w_{mze}, the cheaper biodiesel tips the trade regime of maize from isolation to export.

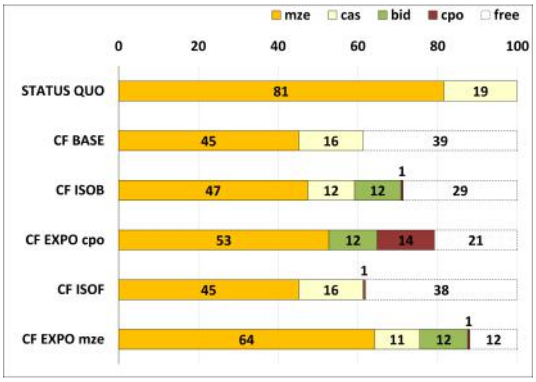

Figure 2: *Share of available area used by scenario and good, in percent*

Due to the exogenous improvement of all individual maize yields, relaxed capacity constraints are apparent in Figure 2, where all counterfactuals remain well below the overall land constraint of 100% reached in *STATUS QUO*. In the north, producer specific binding land constraints return for all producers in *CF ISOB*, *CF EXPO cpo*, and *CF EXPO mze*. This is mostly due to the production of northern goods (biodiesel, cassava, and palm oil, but not maize), as their joint land use approaches the combined land share of northern producers, 26%. While some producers in the rest of Zambia reach their capacity limits in all counterfactuals, overall capacity for maize production is never exhausted in the counterfactuals.

In the counterfactual scenarios, land use for maize continues to dominate. Without the fuel cost reducing production of biodiesel (*CF BASE* and *CF ISOF*), it makes up 45% of available area. With biodiesel, but without exports (*CF ISOB*) it reaches 47%. If exports of palm oil are not banned, palm oil uses 14% of available land, together with biodiesel production squeezing out cassava production in the north of the country. Maize, which in the rest of Zambia does not compete with either palm oil or biodiesel, replaces the missing quantities of cassava on the market and increases its own share of land to 53%. In other scenarios with palm oil, but without its export (*CF ISOB*, *CF ISOF*, and *CF EXPO mze*), 1% of available area suffice to meet domestic palm oil demand. When a world market price of maize at 278 USD/t and low fuel costs due to biodiesel make the export of maize just profitable (*CF EXPO mze*), land use for maize climbs to 64%.

Land use for cassava without competition from biodiesel and exports reaches 16% (*CF BASE* and *CF ISOF*). Improved maize yields reduce this share from previously 19% by rendering any cassava consumption unprofitable that has to be transported to more distant buyers. The production of biodiesel on a scale to replace all fossil diesel (even with additional input demand from exports) needs 12% of available land. This decreases land use of cassava to 12% (*CF ISOB*), 0% with additional competition from palm oil exports (*CF EXPO cpo*), and 11% with maize exports (*CF EXPO mze*).

It stands out, that compared to land use for starchy food crops at 61% in *CF BASE* and *CF ISOF*, this land use increases to 76% in *CF EXPO mze*, due to the introduction of biodiesel.

Market equilibria in the scenarios differ from the baseline (Figure 3). Compared to *CF BASE*, the introduction of cheap, domestic palm oil production replaces inputs in every scenario and reduces its price by 59% if no palm oil is exported (*CF ISOB*, *CF ISOF*, and *CF EXPO mze*). Due to the lower price, demand and the equilibrium quantity rise by 22%. If palm oil exports are not banned (*CF EXPO cpo*), export demand allows prices only to drop by 44% and quantities remaining in the country exceed those in *CF BASE* only by 16%. Palm oil exports amount to 0.828 mn t and do not count towards the domestic equilibrium.

Blends of diesel in the scenarios either use 100% biodiesel (*CF ISOB*, *CF EXPO cpo*, and *CF EXPO mze*) or none (*CF ISOF*). The latter case matches *CF BASE* in quantity and price of the diesel equilibrium. Due to lower costs of biodiesel compared to imported fossil diesel, the biodiesel based *CF ISOB* shows a decline of the price of diesel of 51%. Quantities expand by 17%. Exhibiting additional input demand for exports, each *CF EXPO cpo* and *CF EXPO mze* see a drop in the price of diesel by 49%, and an increase in supply by 17%.[38]

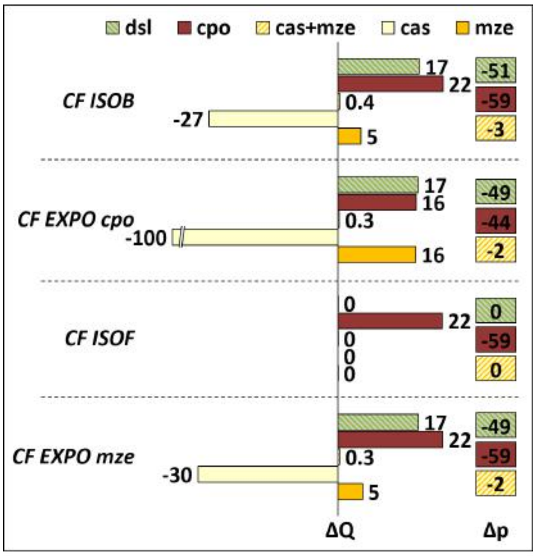

Figure 3: *Relative differences of equilibrium quantities and prices, in percent of CF BASE*

While *CF ISOF* resembles the equilibrium in the starchy foods market of the baseline, the biodiesel based scenarios overall see expansions in quantity and reductions in price. Lacking export, *CF ISOB* shows the clearest effect of the introduction of biodiesel on the starchy foods markets, where quantities increase by 0.4% and price declines by 3%. The small change in overall quantity masks larger shifts between cassava and maize. Replaced by biodiesel, cassava production drops by 27% and maize production expands by 5%. As seen in the *CF BASE* equilibrium, maize production markedly outweighs that

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[38] Compared to *CF ISOB*, the input demand for diesel from exports decreases the equilibrium quantity only in the decimals, but causes a visible difference in price changes in Figure 3.

of cassava, such that the smaller relative increase suffices to reach an overall surplus. In the cases with exports (*CF EXPO cpo* and *CF EXPO mze*), the effects are similar, but smaller overall while more extreme for the separate crops. In both scenarios, overall quantity increases by 0.3% and the price decreases by 2%. In *CF EXPO cpo* palm oil exports require so much northern land, that no cassava is produced and maize compensates the shortfall with an increase of 16%. When maize is exported (*CF EXPO mze*), northern land is not as crucial, but cassava output still plummets by 30%, while the equilibrium quantity of maize increases by 5%. Additionally, 1.072 mn t of maize are exported. Including these exports, the overall supply of starchy foods increases by 32% compared to *CF BASE*. Since the FRA subsidized purchase price of maize is a net-inflow of *WF* to the model, the upper limit of possible sales to the FRA is reached in every counterfactual but *CF EXPO cpo*, where northern producers choose to replace maize cultivation with that of oil palms for either palm oil directly, or for biodiesel. The amount of maize sold to the FRA still reaches 1.582 mn t.

Considering *WF* (Figure 4), all counterfactuals exceed *STATUS QUO* in total *WF* (5.32 bn USD), since they produce maize more efficiently. When exports create additional profits, total *WF* is highest (*CF EXPO cpo* at 6.08 bn USD and *CF EXPO mze* at 5.93 bn USD). Since maize exports in *CF EXPO mze* are only just profitable, *WF* does not differ significantly from *CF ISOB* at 5.93 bn USD. Comparing *CF ISOB* with *CF EXPO cpo*, the pure *WF* effect of palm oil exports is revealed as an increase of 2.6%. Introducing biodiesel to take advantage of an export opportunity at global market prices of maize at 278 USD/t generates a jump in *WF* of 9.4% (*CF ISOF* versus *CF EXPO mze*). Without this export opportunity the introduction of biodiesel (and palm oil) expands *WF* by 9.9% (*CF BASE* versus *CF ISOB*).

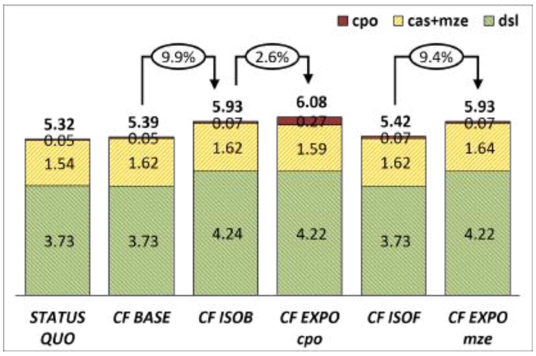

Figure 4: *Welfare by scenario and good, in bn USD*

Without biodiesel, *WF* on the diesel market is 3.73 bn USD. Using only the cheaper biodiesel reduces the fuel price and thus increases *WF* on this market to 4.22 bn USD with supply-reducing fuel input demand for exports and to 4.24 bn USD without it.

WF on the starchy foods market increases from 1.54 bn USD to 1.62 bn USD, once soils are treated for improved maize production (*STATUS QUO* versus *CF BASE*). Due to rather small increases in overall output of starchy foods with the introduction of biodiesel (+0.4%), *WF* in the sector at 1.62 bn USD does not increase markedly (*CF BASE* versus *CF ISOB*). Profits from just profitable maize exports (*CF BASE*) raise sector *WF* slightly to 1.64 bn USD. Exports of palm oil compete with starchy foods for land and reduce their *WF* to 1.59 bn USD, also because of lower subsidized sales of maize to the FRA.

The sole introduction of domestic palm oil production without the production of biodiesel brings an increase in *WF* of this comparatively small sector from 0.05 bn USD to 0.07 bn USD. At prices from the reference season, the export of palm oil raises sector *WF* to 0.27 bn USD.

4.4 Sensitivity

To evaluate how different biodiesel mandates influence land use, the diesel price, and *WF*, I apply *CF ISOB* with μ ranging from 0% to 100%, growing in single percentage point increments (Figure 5).[39]

It is apparent that *WF* increases with μ. A comparison of the extremes of μ at 0% and 100% shows an increase in *WF* of 9.4% from 5.42 to 5.93 bn USD, while a more moderate

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[39] The figure interpolates values between increments.

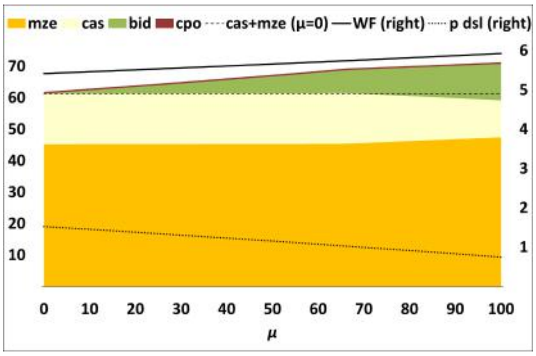

Figure 5: *Total welfare, diesel price, and share of available area used per good, all by μ (CF ISOB), in percent (left and bottom axis), in bn USD and USD/l (right axis)*

μ at 10% raises WF by 0.9%. The relationship is almost linear.

The growth of WF is plausible, since the use of biodiesel replaces costly fossil diesel imports and lowers fuel input costs, as indicated by the constantly decreasing price of diesel. The WF maximizing endogenous price of diesel reacts to decreasing costs of diesel, which the blender forms as a weighted average of the costs of biodiesel and fossil diesel. The diesel price at $\mu = 0\%$ is 1.53 USD/l and decreases close to linearly to 0.75 USD/l at $\mu = 100\%$. The moderate μ of 10% generates a diesel price of 1.45 USD/l.

Initially, expanding μ is not constrained by availability of arable land in the north of Zambia and even at higher μ, changes in land use are small between goods. Total land use increases from 61.8% to 71.3% with μ, mostly due to biodiesel. Barely noticeably, total area of starchy food crops initially grows due to lower fuel costs (combined cassava and maize area surpasses the dashed line). At μ of 65% it gains a maximum of 0.2 percentage points compared to μ at 0% and starts declining.

Beginning at μ of 69%, less land is dedicated to starchy food crops than without any use of biodiesel (combined cassava and maize area drops below the dashed line). Land use shifts from cassava to biodiesel feedstock, due to limited suitable land in the north.

At the same time, land use by maize rises more steeply with μ, because less efficient maize areas, that so far have not supplied the market, become profitable thanks to the lower fuel price and replace the cassava producer. Hence, prices of starchy foods decrease and demand grows (Section 4.3). Because maize is higher yielding (t/ha) than cassava, the overcompensation of declining cassava production by maize is only partial in terms of land use.[40] Combined land use continues under its initial level with μ at 0%.

Land use for palm oil is fairly constant at a low level, averaging 0.5% over the whole range of μ.

5 CONCLUSION

The preceding analyses use a welfare maximizing partial equilibrium model for food, fuel, and fuel feedstock in Zambia to scrutinize a range of scenarios regarding the interaction between food crops and biodiesel.

The general discussion on biofuel stresses the competition between fuel feedstock and food crops for arable land. The fact that fuel is also an input for the production and transport of food is less prominent. Considering both aspects, I introduce a setting where the latter effect leads to an increase in food production. If biofuel is cheaper than fossil fuel, it lowers the costs of production and transport of food, causing an expansion in food supply. Given favorable global market prices, reduced fuel costs allow exports, causing even bigger food supply and an increase in land use for food crops.

Necessary circumstances for this setting include underutilized agricultural capacity, high fuel prices and transport costs, and low exports of food. I model the setting for Zambia, because it exhibits all of these conditions. In this context fuel is represented by diesel and biodiesel, food by the two starchy staple foods cassava and maize, and biofuel feedstock by palm oil, which is also used for other direct consumption.

To model the underutilized agricultural capacity, I consider yield potential for maize from improved soil acidity management and increased fertilizer use. A counterfactual baseline implementing these improvements serves

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[40] Due to constant yields, output relates linearly to the area of each producer.

as a benchmark to evaluate different counterfactual biodiesel scenarios.

Compared to the baseline, model results show that replacing all imported fossil diesel with biodiesel reduces the diesel price by 51%. Therefore, reduced transport and production costs increases food supply (cassava and maize combined) by 0.4% and decreases their price by 3%. These fuel price induced changes are moderate due to the small share of fuel costs in the cost of Zambian maize and cassava produced by smallholders with limited mechanization. Overall welfare expands by 9.9%. An export case, in addition, considers an elevated world market price of maize that allows just profitable exports. Here, diesel prices fall by 49% and overall welfare expands similarly by 9.9%. Domestic food supply increases by 0.3%, and prices of starchy foods drop by 2%. Food supply including exports grows by 32%, causing an expansion in the use of available land for food crops from 61% in the baseline to 76%.

In a sensitivity analysis not considering maize exports, I vary the counterfactual share of biodiesel in fuel. The analysis shows that the price of the fuel blended from fossil and biodiesel steadily decreases with an increasing share of biodiesel, causing a similarly steady increase in welfare. It also shows how competition for land only becomes a binding constraint with blends of ≥65% biodiesel and only causes land use for starchy foods to fall below its level without biodiesel, when blends reach ≥69% biodiesel.

Beyond the analyses of welfare and price effects at hand, import substitution for basic goods like diesel and palm oil may have additional national advantages, like increased local employment and greater stability and independence of supply.

Considering fully developed, operational counterfactual sectors, the analyses show the general welfare benefit of introducing biodiesel in the modeled markets. The analyses do not include the implementation of the counterfactual sectors and therefore, do not involve an adjustment period with initial needs for financing. Potentially large shifts in employment in the affected sectors and in public finances during the adjustment period may also be of political concern. Furthermore, data with finer geographic and temporal granularity would allow the additional modeling of sub-seasonal and provincial effects.

Looking forward, the evaluation of the climate impact of the depicted scenarios may be of interest. An extension of the analyses may map greenhouse gas emission parameters to actions in the model. The resulting emission flows may be priced into the modeled equilibria, for example using CDMs.

Besides Zambia, several other landlocked African countries display the requirements for the analyzed setting, potentially allowing an increase in welfare for millions of people, if biofuels help to unlock the agricultural potential of these countries. Thus, it would be interesting to apply this analysis to other promising countries.

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