AGRICULTURAL ECONOMICS

Agricultural Economics 48 (2016) 1–15

Leveling the field for biofuels: comparing the economic and environmental impacts of biofuel and other export crops in Malawi

Franziska Schuenemann[a,*], James Thurlow[b], Manfred Zeller[a]

[a]*Institute of Agricultural Sciences in the Tropics, University of Hohenheim, Stuttgart, Germany*
[b]*International Food Policy Research Institute, Washington DC, USA*

Received 2 August 2015; received in revised form 8 August 2016; accepted 16 August 2016

Abstract

Biofuels often raise the specter of food insecurity, water resource depletion, and greenhouse gas emissions from land clearing. These concerns underpin the "sustainability criteria" governing access to European biofuel markets. However, it is unclear if producing biofuels in low-income countries does exacerbate poverty and food insecurity, and moreover, whether the sustainability criteria should apply to all agricultural exports entering European markets. We develop an integrated modeling framework to simultaneously assess the economic and environmental impacts of producing biofuels in Malawi. We incorporate the effects of land use change on crop water use, and the opportunity costs of using scarce resources for biofuels instead of other crops. We find that biofuel production reduces poverty and food insecurity by raising household incomes. Irrigated outgrower schemes, rather than estate farms, lead to better economic outcomes, fewer emissions, and similar water requirements. Nevertheless, to gain access to European markets, Malawi would need to reduce emissions from ethanol plants. We find that biofuels' economic and emissions outcomes are generally preferable to tobacco or soybeans. We conclude that the sustainability criteria encourage more sustainable biofuel production in countries like Malawi, but are perhaps overly biased against biofuels since other export crops raise similar concerns about food security and environmental impacts.

JEL classifications: D58, O13, Q18

Keywords: Biofuels; Economic growth; Food security; Water; Malawi

1. Introduction

Climate change, combined with population and economic growth, are placing tremendous pressure on natural resources. Managing these stresses requires a better understanding of the linkages between food, energy and water systems. Biofuels are a prime example of how advances in one system may come at the expense of others. Producing biofuels in developing countries could raise incomes and reduce dependence on imported fossil fuels (Msangi and Evans, 2013). However, clearing lands for biofuel crops generates greenhouse gas (GHG) emissions (Fargione et al., 2008) and might worsen food insecurity by diverting resources from food production. Biofuels' greater use of water resources relative to fossil fuels is a further concern (Berndes, 2002).

Understanding biofuel's economic and environmental trade-offs is challenging, not least because evidence on the effects of biofuels is mixed. While the spike in global food prices in the late 2000s was partly attributed to global biofuels (Rosegrant et al., 2008), a more recent review by Zilberman et al. (2013) found no definite direction of impact. National studies also find that higher incomes from biofuels can offset higher food prices and *improve* food security (Arndt et al., 2010; Arndt et al., 2012; Ewing and Msangi, 2009; Negash and Swinnen, 2013). Finally, while Berndes (2002) projects that the water used by bioenergy crops will eventually equal that of existing crops, the conclusion of this and other studies is that there is enough water available *globally* to expand biofuel production (De Fraiture et al., 2008). Despite this mixed evidence, one conclusion that can be drawn from the literature is the need for more context-specific and integrated analysis.

Economic and environmental trade-offs also have major implications for biofuel policy. Many developing countries see biofuels as an export opportunity. But this hinges on gaining access to European Union (EU) markets, where preferential trade agreements enhance competitiveness and biofuel mandates ensure import demand. In response to concerns over

*Corresponding author. Tel.: +49-711-45923301; fax: +49-711-45923934. *E-mail address*: franziska.schuenemann@uni-hohenheim.de (F. Schuenemann).

 DOI: 10.1111/agec.12335

biofuels, the EU introduced "sustainability criteria" that impose strict conditions for accessing biofuel markets (EC, 2010). By 2018, biofuels in the EU will be required to generate 60% fewer GHG emissions per liter than fossil fuels. Other criteria include avoiding excessive water use and food crop displacement. Governments in developing countries therefore need to know *in advance* how producing biofuels will affect emissions, food security and water use, and whether the EU's sustainability criteria preclude certain biofuel production arrangements.

Despite the need for integrated analysis, most biofuel studies are sector-specific or focus on specific outcomes, such as food production and prices, or land use change and GHG emissions (see, e.g., Searchinger et al., 2008; Timilsina et al., 2012). This overlooks linkages between food, energy and water systems, and between biofuel industries and the rest of the economy. To address this limitation, we build on recent studies that use country-level computable general equilibrium (CGE) models to estimate the impacts of biofuel production on economic growth and poverty (Arndt et al., 2010, 2012) and GHG emissions (Thurlow et al., 2015). We extend this approach to include a more detailed treatment of the agricultural and natural resources required to produce biofuels vis-à-vis other crops. The CGE model is linked to biophysical models that estimate crop water requirements, and GHG emissions from direct and indirect land use change. The integrated modeling framework is applied to Malawi, where the government is debating whether to promote biofuels over other export crops. We compare sugarcane-ethanol production under different farming systems, including smallholder versus estate farms on irrigated versus rainfed lands.

An important limitation of recent CGE-based studies is that they assumed that the "*status quo*" is the correct counterfactual for assessing biofuel impacts. These studies allowed new lands to be cleared for growing biofuel crops and this explained some of the resulting increases in national incomes. However, if cleared lands are not used for biofuels then they could be used for other crops. The correct counterfactual should assume that uncultivated lands do not remain idle in the absence of biofuels. This has important policy implications. The EU's sustainability criteria only apply to biofuels even though producing nonbiofuel crops also has economic and environmental implications. The EU has therefore "raised the bar" on biofuel exports from developing countries, but it has also created an uneven "playing field." By comparing biofuels to other crops, our study can determine if biofuels from Malawi are of particular concern, or if the sustainability criteria are overly biased against biofuels and so should either be relaxed or applied to other agricultural exports.

The article is structured as follows. Section 2 briefly describes the Malawian economy and the role of sugarcane and ethanol. Section 3 describes our integrated suite of models and Section 4 presents our simulation results. We conclude by summarizing our findings and discussing their implications for biofuel policy in Malawi, the EU, and elsewhere.

2. Biofuels in Malawi

2.1. Food, energy, and water systems

Agriculture accounts for a third of Malawi's gross domestic product (GDP) and four-fifths of employment. Most farmers are poor smallholders growing food crops for subsistence, although many also grow tobacco, which is Malawi's main export. Due to declining global tobacco demand, Malawi's government is searching for alternative export crops and biofuels is one of the options being considered (GOM, 2012). Malawi also imports its fossil fuels and so biofuels could help reduce severe foreign exchange constraints.

There are strong linkages between Malawi's food, energy, and water systems. A quarter of the country is covered by Lake Malawi and so irrigation potential is high and water scarcity should be a minor concern. However, most smallholders practice rainfed farming and Malawi experiences frequent droughts causing substantial economic losses (Pauw et al., 2011). Irrigation infrastructure is unaffordable for most smallholders and only 4% of cropland is irrigated (SMEC, 2015). Malawi's electricity supply mainly comes from hydropower and so reductions in dam water levels could lead to electricity shortages.

There is competition over scarce land resources. Malawi is the second most densely populated country in Africa and the average smallholder cultivates less than 1 hectare. Agricultural land expansion is therefore severely constrained and so any new export crop is expected to cause some displacement of existing crops on smallholder lands.

2.2. Sugarcane-ethanol

A biofuel export strategy in Malawi would start from an established base. Malawi has produced sugarcane since the 1960s. Today, two large estate farms grow 80% of the feedstock with the rest produced via smallholder outgrower schemes. Malawian sugarcane is almost entirely irrigated and, thanks to favorable agroclimatic conditions, achieves yields of around 100 metric tons per hectare, which is high by international standards.

Ethanol production from sugarcane started in the late 1980s. Malawi introduced a 10–20% petrol–ethanol blending mandate, but is still far from achieving this target.[1] In 2010, only 18 million liters of ethanol were produced compared to 360 million liters of imported petroleum. Ethanol prices are pegged to the petroleum prices, making locally blended and imported petroleum equally expensive.

Malawi could export biofuels to the EU and the Southern African Development Community (SADC). Malawi has preferential access to EU markets through the "Everything but Arms Initiative" and is part of SADC's Free Trade Area. Foreign investors have shown interest in producing biofuels in Malawi (GOM, 2012). One constraint is the availability of

[1] The typical blending ratio for petrol in Malawi is 10% ethanol and 90% petrol (Mitchell, 2011).

lands suitable for sugarcane. Kassam et al. (2012) estimate that 14,000 hectares of *uncultivated* land is available for rainfed sugarcane. Meanwhile, Malawi's irrigation investment plan intends to grow around 50,000 hectares of *irrigated* sugarcane (SMEC, 2015). Realizing Malawi's full irrigation potential, which Watson (2011) estimates at 300,000 hectares, would require substantial investments. Land availability is therefore a major constraint to biofuel production in Malawi.

2.3. Ethanol production technologies

Malawi's export strategy intends to expand sugarcane production by 75,000 hectares (GOM, 2012). This is only 2% of total crop land and is therefore unlikely to have economywide implications. We simulate a more ambitious biofuel export strategy in order to more accurately gauge economywide impacts. However, the outcomes estimated in our analysis are roughly proportional to the scale of biofuel expansion.

Three broad biofuel options are available to Malawi. Table 1 shows the production technologies used to produce 1,000 million liters ethanol per year, assuming a conversion ratio of 70 L of ethanol per metric ton of feedstock. One option continues to grow sugarcane on estate farms, where irrigated farming systems achieve high yields of 108 tons per hectare. This would require 132,000 hectares of land. Another option would use smallholder outgrower schemes that are either irrigated or rainfed. On average, irrigated smallholders obtain 99 tons per hectare, which is close to estate farm yields and therefore has similar land requirements (i.e., 144,000 hectares). Rainfed smallholders only obtain 42 tons per hectare and so require 340,000 hectares of land. Given Malawi's land constraints, the choice of technology or farming system will greatly influence the extent of land clearing and/or crop displacement.

Table 1
Sugarcane-ethanol production technologies

	Input requirements per 1,000 million liters of sugarcane-based ethanol		
	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers
Liquid yield (L/mt)	70.0	70.0	70.0
Feedstock required (1,000 mt)	14,286	14,286	14,286
Land yield (mt/ha)	108.0	99.0	42.0
Land required (ha)	132,000	144,000	340,000
Workers employed (people)	49,271	53,669	100,634
Feedstock	48,899	53,298	100,263
Processing	371	371	371
Labor yield (people/mL)	49.3	53.7	100.6
Foreign capital requirements (units)	23,568	12,142	9,984
Feedstock	13,584	2,158	0
Processing	9,984	9,984	9,984
Capital yield (units/mL)	23.6	12.1	10.0

Source: Own estimates using farm budget survey data (Herrmann and Grote, 2015) and processing cost estimates (Quintero et al., 2010).

Technologies described in Table 1 were derived from various sources. Information on smallholder production is from a recent survey of sugarcane outgrowers (Herrmann and Grote, 2015). Estate farm technologies are extracted from Malawi's Annual Economic Survey (NSO, 2014). Ethanol processing costs are from a study of processing plants in Tanzania by Quintero et al. (2012), updated to include Malawian feedstock and labor costs. Malawi currently produces ethanol from molasses at two low-capacity processing plants. We assume that better processing technologies would be used to expanded biofuel production, and that the same technology would be used irrespective of the farming system supplying the feedstock.

Large-scale ethanol processing is not particularly labor-intensive (Table 1). Most jobs created in the biofuel industry are in feedstock cultivation. Estate farms are less labor-intensive than outgrower schemes and so employment and wage outcomes will vary by farming system. Total ethanol production costs amount to US$0.63 per liter, which is competitive with imported petroleum. Even with recent price fluctuations, petroleum prices in Malawi have not fallen below US$1 per liter. In global markets, Malawian ethanol is only profitable at a crude oil price of US$77 per barrel.[2] However, Malawi is exempt from EU ethanol tariffs (about US$0.19 per liter) and this makes Malawi's ethanol supply price comparable to those of Brazil (US$0.47) and the United States (US$0.46) (Arndt et al., 2012). The EU's biofuel mandate and favorable trade policies are prerequisites for Malawi's biofuel export strategy.

In the next section, we develop an integrated modeling framework that incorporates the different biofuel technologies and evaluates how the choice of farming system influences the economic and environmental impacts of producing biofuels in Malawi.

3. Measuring economic and environmental impacts

CGE models are essential when evaluating large-scale interventions that are expected to have economywide implications. The Malawi CGE model is linked "top-down" to two natural resource models that measure environmental impacts: (i) a crop model that estimates crop water use and (ii) a carbon accounting model that estimates GHG emissions from land use change.

3.1. Measuring economywide impacts

We use the recursive dynamic CGE model described in Diao and Thurlow (2012) to measure the economic impacts of

[2] Malawian biofuel is profitable at current oil price projections of US$88 per barrel or higher from 2020 onwards (IEA, 2015). Including a shadow value for carbon (via global emissions trading) reduces Malawi's US$77 threshold oil price. For example, Kossoy et al. (2015) estimate that a carbon price of US$100 per ton CO_2eq is needed to limit global warming to 2°C. When applied to our biofuel scenarios, the carbon savings relative to fossil fuels could make Malawi competitive at an oil price of US$54 per barrel.

producing biofuels.[3] Producers and consumers in the model maximize profits and utility and interact in factor and product markets. Production functions in each sector determine output levels and allow imperfect substitution between factors based on their relative prices. Composite factors are combined with intermediate inputs using fixed input–output relationships. There is also substitution between domestic, import and export markets, with the decision on how much to trade based on relative domestic and foreign prices (inclusive of taxes and transaction costs). Malawi is a small country and so world prices are fixed.

The model is calibrated to a 2010 social accounting matrix (SAM) (Pauw et al., 2015) that includes information on production technologies for 58 sectors. Labor is separated by three education levels and rural and urban areas. Crop land is separated into small, medium, and large smallholders and large-scale estates.[4] Given Malawi's land and labor constraints during peak production periods, factors are assumed to be fully employed but mobile across sectors. Only capital is sector-specific.

The distributional impacts of biofuel production are captured by separating households into representative groups based on location (rural or urban), farm size (small, medium, or large) and per capita consumption quintiles. Households can produce for their own consumption or engage in product markets. Households are the main owners of land, labor, and capital, and incomes are used to either consume goods, pay taxes, or save. Consumption is determined by a linear expenditure system of demand with income elasticities estimated using Malawi's 2010–2011 Integrated Household Survey (IHS3) (NSO, 2012). Changes in poverty rates are estimated following the microsimulation approach in Arndt et al. (2012). Households in IHS3 are mapped to household groups in the CGE model. Proportional real consumption changes from the CGE model are passed down to households in the survey, where poverty rates are recalculated using the official poverty line.

Three "closure rules" maintain macroeconomic consistency. First, foreign capital inflows are fixed (beyond what is needed to expand biofuels production) and the exchange rate adjusts to equate supply and demand of foreign exchange. Second, private savings rates are fixed and so rising incomes lead to higher savings and investment. Third, government tax rates and recurrent spending growth are fixed, and the recurrent deficit adjusts to balance total revenues and expenditures. The domestic price index is the model's numeraire.

The model is solved annually over the 10-year period, 2010–2020. Parameters are updated between periods based on long-term trends in factor supplies, total factor productivity, population, government spending, and foreign capital inflows. Capital stocks in each sector are updated each year to reflect depreciation and previous-period investment. Sectors with above-average profits receive a larger share of new capital stocks than their share of installed capital.

3.2. Simulating biofuels production

Three new sugarcane sectors are added to the model based on the production technologies summarized in Table 1. Each sugarcane feedstock sector has its own ethanol processing sector. Production in the biofuel sectors is initially fixed at effectively zero. We then expand the amount of capital invested in a particular ethanol processing sector causing output to expand and drawing in factors and intermediate inputs. The latter includes sugarcane feedstock, which has its own input requirements. Ethanol production in each scenario is gradually increased until it reaches 1,000 million liters per year by the end of the 10-year simulation period. Capital in the biofuel sectors is assumed to be foreign-owned, and so a "foreign capital" factor is inserted into the model that is only used in the biofuel sectors. All profits earned by this capital are repatriated and include repayment for irrigation equipment.

We assume that all new ethanol produced in Malawi is exported. In reality, some may be used to meet the domestic blending mandate. However, as discussed below, demand for imported petroleum in our baseline scenario reaches 587 million liters by 2020. Even if Malawi achieved its 20% blending mandate, this would only require 12% of the 1,000 million liters of ethanol produced in the model in 2020. Local blending mandates do not alter the fact that most of the ethanol produced in our simulations would need to be exported. Fortunately, ethanol and petroleum are close substitutes and so there is little difference from a macro-accounting perspective between (i) exporting ethanol and using the foreign exchange to pay for imported fuels and (ii) reducing fuel imports by redirecting ethanol to domestic markets and forgoing the foreign exchange earnings. This symmetry means that, even though we simulate biofuel exports, our results would be largely unchanged if some locally produced biofuels are used to meet domestic mandates.

Two rounds of scenarios are run for each production technology shown in Table 1. The first scenarios assume that 132,000 hectares of new land are cleared and used to grow biofuel feedstock, and this increases total land supply in the model. This is exactly the amount of land needed by estates to produce the targeted level of ethanol and so there is no need to displace existing crops. In contrast, the smallholder scenarios require more than 132,000 hectares of land and so there is crop displacement. Imposing binding land constraints ensures that our results are not biased in favor of more land-intensive smallholder production options.

The second round of scenarios assumes that only 14,000 hectares of land can be cleared, which is consistent with the suitability assessment in Kassam et al. (2012). Competition over scarce land resources and the level of crop displacement become

[3] The model's variables and equations are provided in Tables A1 and A2 in the Model Appendix.

[4] The model aggregates family-owned and rented crop land. As with owner-occupied dwellings in national accounts, land value-added is paid to smallholders assuming that they rent their lands from themselves. For more information on land in the SAM and CGE model, see Pauw et al. (2015) and Diao and Thurlow (2012).

Table 2
Biofuel and existing crop production technologies, 2010

	Production		Water use		Labor		Value-added or GDP per unit of input	
	Area (1,000 ha)	Yield (mt/ha)	Total (1,000 m^3)	Intensity (m^3/ha)	Intensity (people/ha)	Land (per ha)	Labor (per person)	Water (per m^3)
Existing crops	4,179	2.7	11,030	2,639	0.30	300	1,008	114
Maize	1,696	2.0	4,146	2,444	0.30	350	1,155	143
Other cereals	202	1.0	702	3,473	0.41	349	845	101
Root crops	441	4.7	1,095	2,480	0.22	260	1,177	105
Pulses	705	0.7	1,625	2,305	0.12	143	1,189	62
Horticulture	496	3.5	1,633	3,293	0.66	364	551	110
Oilseeds	335	0.9	889	2,653	0.08	115	1,516	43
Export crops	304	9.9	941	3,094	0.36	504	1,394	163
New sugarcane feedstock								
Irrigated estates	0	108.0	0	10,212	0.37	918	2,483	90
Irrigated outgrowers	0	99.0	0	9,509	0.37	907	2,457	95
Rainfed outgrowers	0	42.0	0	5,057	0.29	430	1,457	85
New reference crops								
Tobacco	0	1.2	0	2,404	0.52	632	1,221	263
Soybeans	0	1.2	0	3,721	0.39	418	1,072	112

Source: Own estimates using production data from FAOSTAT; employment data from IHS3 (NSO, 2012); value-added data from the 2010 social accounting matrix (Pauw et al., 2015); and estimated water use from the process-based crop models (see Section 3).

more pronounced. Total land and labor supplies are fixed and so nonbiofuel sectors may contract depending on their relative factor intensities. Table 2 compares the technologies of biofuel and other crops in Malawi. On average, existing crops generate lower GDP per hectare and worker than the new sugarcane crops. Reallocating resources to biofuels should therefore lead to an increase in average value-added per hectare and worker. These technology differences between crops largely determine the economic outcomes and crop displacement effects in our simulations.

3.3. Estimating crop water use

Results from the CGE model are passed down to crop models that calculate crop water use. Sugarcane is a relatively water-intensive crop and so producing biofuels is expected to increase consumptive water use. Irrigation further increases water use since some water is lost due to inefficient irrigation management. We adopt a "yield response to water" approach (Doorenbos and Kassam, 1979), as reflected in the equation below:

$$\left(1-\frac{Y_a}{Y_m}\right) = K_y\left(1-\frac{ET_a}{ET_m}\right),$$

where Y_a and Y_m are actual and maximum potential yield (tons per hectare); K_y are crop-specific yield response factors; and ET_a and ET_m are actual and maximum potential evapotranspiration (millimeters per year). The model assumes a linear relationship between relative yield declines and relative water deficits, where the latter is the ratio of actual to potential evapotranspiration. The strength of this relationship depends on crop-specific yield response factors.

Potential evapotranspiration ET_m is the water a plant would use if water were always available. Reference evapotranspiration for a hypothetical grass crop was derived using the Penman–Monteith equation and data from 20 Malawian weather stations for the period 1983–2005. Potential evapotranspiration was calculated by multiplying reference evapotranspiration by a coefficient k_c, which captures crops' unique physiological properties. Coefficients for Malawi are from Allen et al. (1998) and Rosegrant et al. (2012). Actual evapotranspiration ET_a for rainfed and irrigated crops was calculated using daily soil water balances derived from precipitation data and soil data from the Africa Soil Profiles Database. Irrigation water use is computed so as to reduce irrigation frequency while avoiding crop water stress. The models estimate *net* irrigation requirements—they exclude water lost during the irrigation process.

We estimated crop water use during an average weather year in Malawi. Average potential evapotranspiration and potential yields were compared to observed yields in the CGE model to back-calculate actual evapotranspiration or water use. Table 2 summarizes our results and confirms that sugarcane is particularly water-intensive.[5] Irrigated estate sugarcane, for example, consumes four times more water per hectare than the average for existing crops. These numbers are used to calculate how the water intensity of agriculture in Malawi changes following a simulated increase in biofuel production in the CGE model.

[5] These are approximate water use estimates since our linear crop model may not capture water-yield responses during extreme weather events.

3.4. Measuring greenhouse gas emissions

Land use change in the CGE model affects both crop water requirements and GHG emissions. The "sustainability criteria" require GHG emissions from biofuels to be 60% lower than fossil fuel emissions. The default average life cycle GHG emission of petroleum is 2.92 kg of carbon dioxide equivalents per liter ($kgCO_2eq/L$). If Malawi wants to export to EU markets then the maximum permissible emissions from ethanol production is 1.17 $kgCO_2eq/L$.[6] However, Dunkelberg et al. (2013) estimate that emissions from current ethanol-molasses production in Malawi is 4.04 $kgCO_2eq/L$. Most of these emissions come from unsustainable handling of waste products and coal heating in ethanol processing. The authors estimate that if energy were derived from waste products, which is similar to the assumption in Quintero et al. (2012), then emissions drop to 2.05 $kgCO_2eq/L$, of which 1.15 $kgCO_2eq/L$ is from processing. We use this estimate of processing emissions in our scenarios, and then add emissions from land clearing and feedstock production.

Feedstock emissions are estimated using a model called "Ex-ante Carbon-balance Tool" (EX-ACT) (Bernoux et al., 2011). This is a land-based accounting tool that calculates the carbon balance from GHG emissions and carbon sequestration in the soil following changes in land use and management. Soil sequestration values for Malawi come from the World Bank's Soil Carbon Sequestration Geodatabase, and the model is calibrated to the tropical conditions and soil types prevalent in Malawi's southern and central regions where sugarcane production is likely to occur.

Land clearing for sugarcane in the CGE model leads to direct land use change and the displacement of other crops.[7] We assume that grasslands are cleared since deforestation generates emissions that far exceed EU thresholds. Grassland conversion emits 12.9 tCO_2eq/ha, half of which are once-off emissions when lands are first cleared. When sugarcane displaces existing crops, then the net emissions depend on the inputs used to grow each crop as well as the crops' soil organic carbon sequestration (SOC) potential. Two reference crops are used when estimating changes in net emissions. For displaced food crops, we use the SOC value of maize (0.617 tC/ha/yr) since this is Malawi's main staple crop. For export crops, we use the SOC value of soybeans (0.839 tC/ha/yr) since this is one of the most affected crops in our simulations. Irrigation is more input-intensive and so generates more emissions. Sugarcane itself, however, has heavier biomass and so is a carbon sink relative to the reference crops, with a SOC value of 1.220 tC/ha/yr. This means that, without land clearing, switching from existing crops to sugarcane leads to lower net emissions.

[6] Emissions from ethanol fuel use are not included since these are set to zero in EU calculations. These are a large part of petrol emissions and should ideally be included in a complete life cycle analysis of ethanol.

[7] We implicitly capture emissions from indirect land use change (ILUC) in the model, since emissions from land clearing are the same regardless of whether cleared lands are used for biofuel or other crops.

4. Results

4.1. Baseline scenario

The CGE model's baseline scenario tracks recent trends in population and economic growth. Labor and land supplies grow at 2.0% and 1.7% per year, respectively, and total factor productivity grows at 2.7% per year. This generates annual GDP growth of 4.7% (see Table 3) and this is fairly evenly distributed across sectors. Note that the baseline scenario is only of marginal interest for our analysis, since it merely provides a reference for measuring the impacts of expanding biofuel production. In discussing the impacts of biofuel crops, we first compare biofuels to this "*status quo*" baseline scenario (as in previous studies), and then later to alternative reference scenarios that allow for the expansion of other export crops.

4.2. Producing biofuels on estate farms

We initially focus on the first three biofuel scenarios in which 132,000 hectares of uncultivated lands are cleared for sugarcane-ethanol. The third column in Table 3 reports final year deviations from baseline for the Irrigated Estate scenario. There is no direct crop displacement in this scenario since newly cleared lands exactly equal the amount of land required to grow feedstock on estate farms (see Table 1). There is, however, indirect land use change. Lands are reallocated from existing export crops (e.g., tobacco) to food crops (e.g., maize). This is driven by biofuel exports, which grow rapidly and cause the real exchange rate to appreciate, thereby reducing the competitiveness of nonbiofuel export crops in foreign markets. To some extent, Malawi exchanges one export crop for another. However, since value-added per hectare for sugarcane is higher than it is for existing export crops (see Table 2), switching to biofuels leads to higher agricultural GDP. The clearing of new lands also increases the supply of productive resources. Higher incomes and an appreciated exchange rate lead to more land allocated to food production and lower real food prices. Unlike in the Arndt et al. (2010) study for Mozambique—a country with few nonbiofuel export crops—we find that biofuels production in Malawi might eventually lead to improved food availability.

Table 4 reports impacts on labor and households. Bringing newly cleared lands into production increases demand for labor on estate farms. However, food crops and estate farms are less labor-intensive than displaced export crops (see Table 2), causing agriculture's overall labor share to decline. Rural wages still increase due to higher agricultural GDP, but the gains in urban wages are larger. Urban workers benefit from rising labor demand in ethanol processing sectors, but this is more than offset by falling employment in sectors that process existing crops (e.g., tobacco curing). The increase in nonfarm employment and urban wages mainly comes from workers migrating to the trade and business sectors, which benefit from higher incomes and greater demand for nontraded services. Growth in industrial

Table 3
Production and price impacts

	Initial share or value, 2010	Baseline growth rate or total change (%)	Deviation from final year baseline value (%)					
			Biofuel scenarios with land expansion			Biofuel scenarios with land constraints		
			Irrigated estates	Irrigated outgrowers	Rainfed outgrowers	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers
Total GDP growth (%)	100.0	4.7	2.0	1.7	0.9	18	1.4	0.7
Agriculture	32.3	4.6	2.9	3.1	1.5	1.8	2.1	0.4
Food crops	16.6	4.5	1.9	2.9	−0.4	0.0	0.9	−2.7
Export crops	3.1	4.5	22.7	18.4	20.2	21.7	17.5	19.5
Of which nonbiofuels	3.1	4.5	−18.3	−25.8	−29.0	−19.3	−26.7	−29.8
Other agriculture	11.2	4.8	−0.8	−0.5	−0.5	−0.7	−0.3	−0.4
Industry	16.5	5.6	1.2	−1.0	−1.2	1.7	−0.5	−0.7
Of which ethanol	0.0	0.0	∞	∞	∞	∞	∞	∞
Of which electricity	0.8	4.2	23.7	20.4	18.1	23.8	20.6	18.3
Services	51.2	4.5	1.7	1.6	1.3	1.8	1.7	1.3
Change in price indices (%)								
Real exchange rate	1.0	6.0	−2.7	−3.4	−3.2	−2.4	−3.2	−2.8
Real food prices	1.0	4.0	−0.5	−0.4	0.2	−0.3	−0.1	0.6
Total crop land (1,000 ha)	4,233	777	132	132	132	14	14	14
Food crops	3,357	841	72	104	−43	−16	13	−140
Existing export crops	639	−71	−72	−116	−165	−102	−143	−186
Feedstock crops	0	0	132	144	340	132	144	340

Source: Results from the Malawi CGE model.
Note: Biofuels processing grows from a zero base and so growth is infinite.

Table 4
Labor and household impacts

	Initial value or share, 2010	Baseline growth rate or total change (%)	Deviation from final year baseline value (%)					
			Biofuel scenarios with land expansion			Biofuel scenarios with land constraints		
			Irrigated estates	Irrigated outgrowers	Rainfed outgrowers	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers
Agriculture labor share (%)	63.5	64.2	−0.9	1.0	4.4	−1.4	0.6	4.0
Real wage (%)	3725.7	2.6	1.1	1.3	1.0	0.9	1.0	0.7
Rural workers	3,617	2.7	0.7	1.0	1.0	0.4	0.7	0.7
Urban workers	3,835	2.6	1.5	1.6	0.9	1.3	1.4	0.7
Household welfare (%)	425.7	1.6	0.7	1.3	0.6	0.4	1.0	0.2
Farm households	330	1.6	0.2	1.6	0.8	−0.2	1.1	0.3
Nonfarm households	1,019	1.5	1.5	0.8	0.3	1.5	0.7	0.2
Poverty headcount rate (%)	51.0	28.7	−0.1	−2.4	−0.9	0.8	−1.4	0.2
Farm households	55.9	32.1	−0.1	−2.4	−1.0	0.9	−1.4	0.1
Nonfarm households	20.3	7.8	−2.5	−1.6	0.9	−1.3	0.0	2.1

Source: Results from the Malawi CGE and microsimulation models.
Note: Welfare is measured using real consumption expenditure, the initial value is average per capita US$ expenditure. Poverty headcount rate is the share of the population with per capita expenditures below the national poverty line.

GDP is driven by increased electricity generation following the expansion of ethanol processing and irrigated estates, both of which are more energy-intensive than the manufacturing sectors and export crops that they displace.

Ultimately, national GDP is 2% higher in the Irrigated Estate scenario than in the baseline. This positive growth-effect from biofuels is driven by (i) an increase in the level of productive resources in the economy, that is, from newly cleared lands and additional foreign capital; (ii) higher value-added per worker and per hectare of cropland in the biofuel sectors; and (iii) positive spillover or growth linkage effects, for example, incomes from biofuels generating demand for all goods and services. Realizing these medium-term economic gains will impose adjustment costs on the economy, particularly on producers of existing crops and workers in downstream agroprocessing. It may also require additional public investments in the electricity sector, the cost of which is only partially internalized in our model.

The household welfare and distributional effects of producing biofuels on Estate farms are less promising than the macroeconomic results would suggest. Household welfare does not increase by as much as GDP, because the profits from biofuel production are repatriated. Smallholders do not benefit by as much as nonfarm households. This is because smallholders previously produced export crops, like tobacco, but these were displaced by sugarcane grown in estates. Smallholders find themselves growing more food crops and relying more on wages from estate farms, both of which generate less income than the displaced export crops (see Table 2). In contrast, nonfarm households benefit from lower food prices, higher urban wages, and cheaper imports. The reduction in the urban poverty rate (by 2.5 percentage points) is therefore larger than the reduction in rural poverty (by only 0.1 percentage points). Producing biofuels on estate farms reduces poverty and improves food availability, but the benefits for the rural poor are fairly modest.

4.3. *Using outgrower schemes*

Smallholders achieve lower yields and require more land to meet the biofuel production target (see Table 1). The fourth column of Table 3 reports results for the Irrigated Outgrower scenario. Producing sugarcane feedstock now requires 144,000 hectares, but we still only allow 132,000 hectares of new lands to be cleared. This means that biofuels directly displace existing crops. As in the previous scenario, the real appreciation caused by biofuel exports directs all of the displacement onto existing export crops. In fact, the land allocated to food crops increases. The appreciation is larger than in the Irrigated Estate scenario, because more of the on-farm profits from growing sugarcane via outgrower schemes remains with smallholders rather than being repatriated to foreign investors. Higher smallholder incomes also generate greater demand for products that smallholders consume intensively, such as food. The reallocation of land from existing export crops to food crops is therefore larger in this scenario. Higher demand for food also means that real food prices fall by less than in the previous scenario even though the increase in food production is now larger.

The large decline in existing export crops in this scenario leads to larger job losses in downstream processing. This more than offsets the expansion in ethanol processing, leading to lower manufacturing GDP and employment. However, smallholder farming is more labor-intensive than estate farming (see Table 1) and so using outgrower schemes increases agriculture's labor requirements. Overall, agriculture's employment share rises in the Irrigated Outgrower scenario and is matched by higher agricultural GDP growth (see Table 4). Gains in national GDP are smaller in this scenario due to declining industrial GDP. Faster agricultural growth is coupled with larger improvements in household welfare. Outgrower schemes mean that more benefits from producing biofuels accrue to smallholders. It is rural rather than urban households that now experience the largest gains in welfare and poverty reduction.

4.4. *Relying on rainfed production*

In the Irrigated Outgrower scenario above we assumed that foreign investors provided irrigation infrastructure and that smallholders in the outgrower scheme repaid investors over a 10-year period. This explains why irrigated smallholder farms require foreign capital (see Table 1). We now consider the implications of producing sugarcane using smallholder farmers who do not have access to irrigation. Since there is no irrigation, smallholders no longer use foreign capital and do not have to repay investors. However, without irrigation, smallholders achieve much lower yields and require 340,000 hectares of land in order to achieve the ethanol production target. Again, we assume that only 132,000 hectares of new lands can be cleared.

Results are shown in the fifth column of Table 3. The level of crop displacement caused by biofuels is sufficiently large such that there is now a decline in the lands allocated to *both* existing export and food crops, although impacts on the former are still more pronounced. Declining food production leads to higher real food prices. There is still a positive effect on national GDP, but this is now smaller than before because land and labor productivity gains are more modest. For example, value-added per hectare of sugarcane in the Rainfed Outgrower scenario is US$430, which is much lower than the US$907 in the irrigated outgrower scenario (see Table 2). This explains the smaller increase in agricultural GDP. Again, industrial GDP falls slightly because of a contraction in downstream agroprocessing.

Rainfed sugarcane has a higher labor-to-land ratio than existing crops (see Table 2) and so reallocating land leads to a higher average labor intensity for agriculture as a whole. Agriculture's share of employment increases substantially by 4.4 percentage points in the rainfed outgrower scenario. Higher agricultural labor demand helps maintain rural wage growth despite slower agricultural GDP growth. Slower nonagricultural growth, on the other hand, means slower urban wage growth. Household welfare still improves for both rural and urban households, but the gains are smaller than under the Irrigated Smallholder scenario. Urban poverty rates rise because of higher real food prices.

The results from the first three scenarios suggest that biofuels can generate economic growth and reduce poverty. This can be achieved without jeopardizing food security only if feedstock is grown on irrigated lands. Finally, the choice between irrigated estate farms or irrigated outgrower schemes involves a clear trade-off between maximizing national growth or poverty reduction.

4.5. *Environmental impacts and trade-offs*

Table 5 reports the estimated GHG emissions and crop water use associated with the three biofuel scenarios discussed above. The final line in the table shows the amount of water used to grow sugarcane per liter of ethanol produced. Water use is much higher under irrigation. Even assuming a high

Table 5
Emissions and water use

	Biofuel scenarios with land expansion			Biofuel scenarios with land constraints		
	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers
GHG emissions embodied within ethanol (kgCO_2eq/L/yr)						
After 1 year	2.61	2.62	2.31	1.42	1.46	1.00
After 10 years	1.81	1.82	1.52	1.34	1.37	0.91
After 20 years	1.77	1.78	1.47	1.33	1.37	0.91
Decomposition of GHG emissions after first year (kgCO_2eq/L/yr)						
Clearing lands	1.70	1.70	1.70	0.18	0.18	0.18
Displacing crops	0.00	0.04	0.57	0.34	0.40	0.78
Growing feedstock	−0.24	−0.27	−1.11	−0.24	−0.27	−1.11
Processing feedstock	1.15	1.15	1.15	1.15	1.15	1.15
Crop water use (mm^3)						
Total crop water use	1,435	1,435	1,423	1,407	1,407	1,395
Of which feedstock	135	137	172	135	137	172
Change from baseline	137	136	125	109	109	97
Crop water embodied within ethanol (liters/liter)	3,198	3,387	1,720	3,198	3,387	1,720

Source: Results from the Malawi CGE and crop models.
Note: GHG emissions are measured by tons of CO_2 equivalent per liter of ethanol per year.

irrigation efficiency rate of 50%, irrigated smallholder cultivation uses almost twice as much water as rainfed sugarcane (i.e., 3,387 vs. 1,720 L). Rainfed agriculture is most efficient in its water use, but it achieves lower yields and uses more land.

Our estimated water requirements are fairly high. Gerbens-Leeneens and Hoekstra (2009) estimated that Brazil, as the world's largest ethanol producer, uses 2,500 L of water per liter of ethanol. These authors included polluted "grey water" from fertilizers, whereas we consider only crop and irrigation water. Malawi's actual water use may therefore be higher than our estimates. In total, we find that 2 billion cubic meters of water is needed per year to produce 1,000 million liters of ethanol. This appears to be small relative to the 8,400 billion cubic meters of water in Lake Malawi. However, local impacts on small watersheds can be significant. The effects on water levels in Lake Malawi and the Shire River would need to be determined by hydrological water basin models.

Table 5 reports changes in consumptive water used by crops in Malawi relative to the baseline. This includes total crop evapotranspiration, but not the water lost through inefficient irrigation. Rainfed sugarcane uses more water than irrigated sugarcane, that is, 172 and 137 million cubic meters, respectively. This is because, even though rainfed sugarcane uses less water per hectare, it also uses more land. Rainfed sugarcane therefore displaces more crops with lower water needs (see Table 2), thus driving up total evapotranspiration. Overall, sugarcane-ethanol expansion in our simulations increases the water intensity of Malawian agriculture by almost 10% irrespective of which biofuel production technology is used and despite the fact that land area increases by only 2.6%.

We now consider emissions from land use change. In the three biofuel scenarios discussed above we assumed that 132,000 hectares of land are cleared to grow sugarcane. Table 5 indicates that most of the emissions per liter of ethanol are from the once-off clearing of grasslands. Over time, these emissions are spread over a larger volume of ethanol until eventually the emissions per liter are essentially only those from cultivating sugarcane, such as the fossil fuels used for fertilizer, irrigation and transport. The reported emissions are therefore higher in the first year of ethanol production and lower after 10 years.

Processing ethanol in Malawi generates 1.15 tCO_2eq/L, which is close to the EU's 2018 threshold of 1.17 kgCO_2eq/L. Emissions from growing feedstock therefore have to be extremely low in order for Malawi to export to EU markets. Our results indicate that clearing 132,000 hectares of grassland generates 1.70 kgCO_2eq/L in the first year of ethanol production. Although sugarcane is a carbon sink, it cannot offset the emissions from land clearing. Even after 20 years, emissions in the Rainfed Outgrower scenario are 1.47 tCO_2eq/L. If sugarcane is grown on irrigated lands with inputs that directly or indirectly use fossil fuels then emissions are higher at 1.78 tCO_2eq/L.

The potential for Malawian biofuels to help mitigate climate change is hampered by the high carbon debt from land clearing and the emissions from ethanol processing. The latter should be kept in mind when building new processing plants. Dunkelberg et al. (2013) find that if ethanol plants in Malawi switch from coal to energy produced using crop residues, then

Table 6
Comparing biofuels to alternative cash crops

	Deviation from final year baseline value (%)			
	Ethanol (irrigated outgrowers)	Tobacco (rainfed outgrowers)	Soybeans (rainfed outgrowers)	Sugar (irrigated outgrower)
Total crop land (1,000 ha)	5,024	5,024	5,024	5,024
Of which cleared lands	14	14	14	14
Total GDP growth (%)	1.4	0.4	0.0	1.8
Agriculture	2.1	1.2	0.5	2.1
Food crops	0.9	−0.7	−1.3	1.5
Export crops	17.5	17.1	12.2	14.0
Industry	−0.5	0.7	0.7	3.9
Services	1.7	−0.2	−0.5	0.8
Change in price indices (%)				
Real exchange rate	−3.2	−1.0	−0.3	−3.6
Real food prices	−0.1	0.5	0.5	0.1
Household welfare (%)	1.0	0.2	−0.1	1.3
Farm households	1.1	0.4	0.1	1.9
Nonfarm households	0.7	−0.4	−0.4	0.2
Poverty headcount rate (%)	−1.4	−1.1	−0.4	−3.7
Farm households	−1.4	−1.2	−0.4	−3.7
Nonfarm households	0.0	0.3	0.3	−2.3
Total crop water use (mm^3)	1,407	1,333	1,377	1,407
Emissions from feedstock production (tCO_2eq/yr)				
Per hectare after 10 years	1.6	1.7	0.7	1.6
Per additional US$ GDP	1.6	6.4	34.0	1.6

Source: Results from the Malawi CGE and microsimulation models.
Note: Welfare is measured using real consumption expenditure, the initial value is average per capita US$ expenditure. Poverty headcount rate is the share of the population with per capita expenditures below the national poverty line.

the processing emissions become almost negligible. While this would require investments in more sophisticated technologies, it would improve Malawi's chances of meeting the EU's targets.

4.6. Imposing stricter land constraints

The previous scenarios assumed that 132,000 hectares of land are cleared for sugarcane. This may not accurately reflect Malawi's severe land constraints and so might exaggerate growth and welfare gains. This section assumes that only 14,000 hectares of land suitable for sugarcane is cleared. This is consistent with land suitability estimates from Kassam et al. (2012), but is much more conservative than SMEC (2015) or Watson (2011). The final three columns in Table 3 report results for biofuel production under land constraints. Each scenario should be compared to the corresponding scenario that allowed for more land expansion.

We still produce the same targeted level of ethanol as in earlier scenarios. However, stricter land constraints mean that there is greater displacement of existing crops, particularly for export crops. The land allocated to food crops now declines in the Irrigated Estate scenario and is much smaller in the Irrigated Outgrower scenario. Falling food production means higher real food prices. This is clearest in the Rainfed Outgrower scenario, where almost all export crops are displaced and there is a large reduction in lands for food crops.

Average value-added per hectare still rises in the biofuel scenarios due to sugarcane's higher land productivity relative to existing crops. However, the gains in agricultural GDP are smaller because less new land is added to productive resources. Less land also means smaller increases in demand for farm labor and so agriculture's share of employment does not increase by as much (see Table 4). Slower growth in labor demand means smaller wage increases and welfare improvements. The Irrigated Outgrower scenario generates the largest welfare gains for poorer households. In contrast, poverty in the Rainfed Outgrower scenario actually increases due to higher food prices and smaller land productivity and wage gains. The economic tradeoffs between production technologies are starker with stricter land constraints.

As expected, emissions per liter of ethanol are much lower when there is less land clearing (see Table 5). After 10 years, emissions in the Rainfed Outgrower scenario are only 0.91 tCO_2eq/L, which is well below the EU's target of 1.17 tCO_2eq/L. However, rainfed production is not an attractive option given its adverse effects on food production and poverty. The Irrigated Outgrower scenario is preferable from a development perspective, but, even after 10 years, its emissions per liter of ethanol exceed the EU target.

Feedstock water use per liter of ethanol is unchanged in the land constrained scenarios. However, total crop water use declines slightly because of the greater displacement of existing crops. If incremental water use from producing biofuels is used to measure biofuels' water content (i.e., if we deduct displaced crop water use), then additional water use resulting from producing biofuels is 20% lower than in the previous scenarios (e.g., 109/136 = 0.80 for the Irrigated Outgrower scenarios). Yet, even with this more lenient measurement, ethanol's water use in Malawi still exceeds that in Brazil. Overall, our analysis suggests that *both* development and environmental objectives could be achieved if Malawi reduces its emissions from ethanol processing; and if no quantitative restrictions on water use are added to the EU's sustainability criteria.

4.7. Biofuels versus other export crops

So far we have followed the approach of previous studies by comparing biofuel production to a "*status quo*" baseline. Yet Malawi's export strategy (GOM, 2012) suggests that if croplands are not used to grow sugarcane for ethanol, then they might be used to grow other export crops. A more appropriate counterfactual should consider these opportunity costs. We consider three alternative export crops: tobacco, soybeans, and sugarcane grown for refined sugar production (as opposed to ethanol production). Tobacco is a well-established smallholder crop with strong downstream linkages to agroprocessing (i.e., tobacco curing). Soybeans is a relatively new crop that is identified alongside biofuels in the export strategy. Finally, using sugarcane feedstock to produce refined sugar rather than ethanol is an important option given fluctuations in global oil and ethanol prices.

In our new counterfactual "cash crop" scenarios, we assume that the additional tobacco and soybean production and downstream processing make use of Malawi's existing technologies (as captured in the official 2010 SAM). The only difference between sugarcane grown for ethanol and refined sugar is in how the feedstock is processed—the actual feedstock is grown using the same smallholder outgrower schemes (see Table 2).As with biofuels, tobacco, soybean, and sugar refining are entirely financed by foreign capital and all profits are repatriated. To ensure that our scenarios are comparable, we simulate the same 144,000 hectare expansion in crop land devoted to each alternative cash crop and only permit 14,000 hectares of new lands to be cleared. We compare the new cash crop reference scenarios to the earlier irrigated outgrower scenario that produced ethanol.

Table 6 reports results for the Tobacco, Soybean, and Sugar scenarios alongside results from the Irrigated Outgrower ethanol scenario. Agricultural exports increase in all four scenarios, but food production falls in the Tobacco and Soybean scenarios (relative to the baseline). Tobacco and soybeans have high labor-to-land ratios (see Table 2) and so expanding their cropland area draws labor away from food crops. A larger exchange rate appreciation in the Sugar scenario leads to greater displacement of export crops and production of food crops. Agriculture's share of total employment in the Tobacco and Soybean scenarios increases by 5.6 and 4.6 percentage points, respectively, compared to a one percentage point increase in the Irrigated Outgrower scenario and a slight reduction in the Sugar scenario. Both land and labor displacement are important in determining impacts on food production.

Tobacco and soybeans generate less value-added per hectare than sugarcane and so agricultural GDP gains are smaller. All four crops create downstream jobs, but tobacco and soybean processing and sugar refining are more labor-intensive. Agriculture's rising labor-intensity along with the creation of more industrial jobs means that fewer workers migrate to the service sectors. At the same time, the high labor-intensity of sugar refining leads to much larger industrial growth than in the other scenarios. Total GDP is unchanged in the Soybean scenario because of this crop's low land productivity. Agricultural gains are exactly offset by nonagricultural losses. Tobacco production leads to an increase in total GDP, but these gains are smaller than in the Irrigated Outgrower scenario. Overall, using sugarcane for refined sugar leads to a larger increase in total GDP growth than using it for ethanol. This underscores the importance of including opportunity costs in the counterfactual scenario.

Changes in household welfare mirror the changes in total GDP. Farm household poverty declines in both the Tobacco and Soybean scenarios, reflecting the importance of these crops for poorer smallholders in Malawi. However, total welfare gains and poverty reduction are much larger in the two sugarcane-based scenarios. This is consistent with Herrmann and Grote (2015), who found that sugarcane outgrower schemes reduce poverty amongst smallholder farmers in Malawi. Even though biofuels production leads to better economic outcomes than either tobacco and soybeans, we find that the production of refined sugar is even more beneficial in terms of both welfare gains and poverty reduction.

Finally, we compare environmental impacts. Total crop water use in Malawi increases in the Tobacco and Soybean scenarios because these crops use more water per hectare than the crops they displace. Ethanol and refined sugar production are, however, much more water-intensive than tobacco or soybeans. This justifies the concerns about the pressure that biofuels place on scarce water resources. Importantly, emissions per hectare of sugarcane are lower than emissions from tobacco. Sugarcane's emissions per dollar of crop GDP are also lower than either tobacco or soybeans.[8] All alternative cash crops generate positive emissions, but sugarcane's heavy biomass means that it is a larger carbon sink than soybeans and tobacco (i.e., despite sugarcane being irrigated and using more fertilizers).

5. Conclusion

We developed an integrated modeling framework that jointly assesses the economic and environmental impacts of producing

[8] Emissions are from crops cultivation only and exclude possible processing emissions. Estimates suggest that emissions from tobacco curing are higher than those of ethanol processing. No estimates were available for soybeans.

biofuels in Malawi. We find that sugarcane production on large-scale estate farms has the largest positive effect on economic growth. However, irrigated outgrower schemes are more effective at reducing poverty. Smallholders in Malawi that use irrigation achieve sugarcane yields that are similar to those on estate farms, and so the level of GHG emissions per liter of ethanol is similar across these two irrigated farming systems. Reliance on rainfed cropping systems leads to far less favorable food security and poverty outcomes although it does generate lower GHG emissions. There are clear trade-offs between each farming system. Nevertheless, we conclude that irrigated smallholder outgrower schemes operating on existing crop lands is the preferred means of producing biofuels in Malawi.

More generally, we conclude that concerns about the impacts of biofuels on climate change and food security are warranted in the case of Malawi. Producing biofuels in Malawi increases crop water use and GHG emissions. However, similar concerns can also be raised about other export crops. Our analysis for Malawi suggests that growing sugarcane generally leads to better economic outcomes and fewer GHG emissions than tobacco or soybeans—two crops that feature prominently alongside biofuels in Malawi's new export strategy. The EU's sustainability criteria are correct in seeking to "raise the bar" on the environmental standards that must be met by biofuel producers. However, our study also suggests that these criteria are perhaps overly biased against biofuels. A "level playing field" should impose similar economic and environmental standards on all agricultural exports from developing countries like Malawi.

Acknowledgments

This study was funded by the German Federal Ministry for Economic Cooperation and Development (research project "Policies and Institutions for Achieving the Virtuous Food-Energy-Water Nexus in Sub-Saharan Africa"); the United States Agency for International Development via its support of IFPRI's Malawi Strategy Support Program; and the CGIAR Research Program on Policies, Institutions, and Markets (PIM), which is led by IFPRI and funded by the CGIAR Fund Donors. We are grateful for comments received from Karl Pauw (Food and Agriculture Organization) and Tingju Zhu (IFPRI), and two anonymous reviewers.

Model Appendix

Table A1
Model indices, variables, and parameters

Indices			
c	Commodities and activities	h	Representative households
f	Factors (land, labor and capital)	t	Time periods
Exogenous parameters (Greek characters)			
α^p	Production function shift parameter	θ^v	Value-added share of gross output
α^q	Import function shift parameter	π	Foreign savings growth rate
α^t	Export function shift parameter	ρ^p	Production function substitution elasticity
β	Household marginal budget share	ρ^q	Import function substitution elasticity
γ	Nonmonetary consumption quantity	ρ^t	Export function substitution elasticity
δ^p	Production function share parameter	σ	Rate of technical change
δ^q	Import function share parameter	τ	Foreign consumption growth rate
δ^t	Export function share parameter	υ	Capital depreciation rate
ε	Land and labor supply growth rate	φ	Population growth rate
θ^i	Intermediate share of gross output	ω	Factor income distribution shares
Exogenous parameters (Latin characters)			
ca	Intermediate input coefficients	pwm	World import price
cab	Current account balance	qfs	Total factor supply
cd	Domestic transaction cost coefficients	$qgov$	Base government consumption quantity
ce	Export transaction cost coefficients	$qinv$	Base investment demand quantity
ci	Capital price index weights	rf	Factor foreign remittance rate
cm	Import transaction cost coefficients	sh	Marginal propensity to save
cpi	Consumer price index	tf	Factor direct tax rate
cw	Consumer price index weights	th	Personal direct tax rate
ga	Government consumption adjustment factor	tm	Import tariff rate
gh	Per capita transfer from government	tq	Sales tax rate
pop	Household population	wh	Net transfer from rest of world
pwe	World export price		

Continued

Table A1
Model indices, variables, and parameters

Endogenous variables			
AR	Average capital rental rate	QG	Government consumption quantity
FS	Fiscal surplus (deficit)	QH	Household consumption quantity
IA	Investment demand adjustment factor	QI	Investment demand quantity
PA	Activity output price	QK	New capital stock quantity
PD	Domestic supply price with margin	QM	Import quantity
PE	Export price	QN	Aggregate intermediate input quantity
PM	Import price	QQ	Composite supply quantity
PN	Aggregate intermediate input price	QT	Transaction cost demand quantity
PQ	Composite supply price	QV	Composite value-added quantity
PS	Domestic supply price without margin	WD	Sector distortion in factor return
PV	Composite value-added price	WF	Economywide factor return
QA	Activity output quantity	YF	Total factor income
QD	Domestic supply quantity	YG	Total government revenues
QE	Export quantity	YH	Total household income
QF	Factor demand quantity	X	Exchange rate

Table A2
Model equations

Prices	
$PM_{ct} = pwm_c \cdot (1 + tm_c) \cdot X + \sum_c' PQ_{c't} \cdot cm_{c'c}$	1
$PE_{ct} = pwe_c \cdot X_t - \sum_c' PQ_{c't} \cdot ce_{c'c}$	2
$PD_{ct} = PS_{ct} + \sum_c' PQ_{c't} \cdot cd_{c'c}$	3
$PQ_{ct} \cdot (1 - tq_c) \cdot QQ_{ct} = PD_{ct} \cdot QD_{ct} + PM_{ct} \cdot QM_{ct}$	4
$PX_{ct} \cdot QX_{ct} = PS_{ct} \cdot QD_{ct} + PE_{ct} \cdot QE_{ct}$	5
$PN_{ct} = \sum_c' PQ_{c't} \cdot ca_{c'c}$	6
$PA_{ct} \cdot QA_{ct} = PV_{ct} \cdot QV_{ct} + PN_{ct} \cdot QN_{ct}$	7
$cpi = \sum_c cw_c \cdot PQ_{ct}$	8
Production and trade	
$QV_{ct} = \alpha_{ct}^p \cdot \sum_f (\delta_{fc}^p \cdot QF_{fct}^{-\rho_c^p})^{-1/\rho_c^p}$	9
$WF_{ft} \cdot WD_{fct} = PV_{ct} \cdot QV_{ct} \cdot \sum_f' (\delta_{f'c}^p \cdot QF_{f'ct}^{-\rho_c^p})^{-1} \cdot \delta_c^p \cdot QF_{fct}^{-\rho_c^p - 1}$	10
$QN_{ct} = \theta_c^i \cdot QA_{ct}$	11
$QV_{ct} = \theta_c^v \cdot QA_{ct}$	12
$QA_{ct} = \alpha_c^t \cdot (\delta_c^t \cdot QE_{ct}^{\rho_c^t} + (1 - \delta_c^t) \cdot QD_{ct}^{\rho_c^t})^{1/\rho_c^t}$	13
$\frac{QE_{ct}}{QD_{ct}} = (\frac{PE_{ct}}{PS_{ct}} \cdot \frac{(1-\delta_c^t)}{\delta_c^t})^{1/(\rho_c^t - 1)}$	14
$QQ_{ct} = \alpha_c^q \cdot (\delta_c^q \cdot QM_{ct}^{-\rho_c^q} + (1 - \delta_c^q) \cdot QD_{ct}^{-\rho_c^q})^{-1/\rho_c^t}$	16
$\frac{QM_{ct}}{QD_{ct}} = (\frac{PD_{ct}}{PM_{ct}} \cdot \frac{(1-\delta_c^q)}{\delta_c^q})^{1/(1+\rho_c^t)}$	17
$QT_{ct} = \sum_c'(cd_{cc'} \cdot QD_{c't} + cm_{cc'} \cdot QM_{c't} + ce_{cc'} \cdot QE_{c't})$	18
Incomes and expenditures	
$YF_{ft} = \sum_c WF_{ft} \cdot WD_{fct} \cdot QF_{fct}$	19
$YH_{ht} = \sum_f \omega_{hf} \cdot (1 - tf_f) \cdot (1 - rf_f) \cdot YF_{ft} + gh_h \cdot pop_{ht} \cdot cpi + wh_h \cdot X$	20
$PQ_{ct} \cdot QH_{cht} = PQ_{ct} \cdot \gamma_{ch} + \beta_{ch} \cdot ((1 - sh_h) \cdot (1 - th_h) \cdot YH_{ht} - \sum_c' PQ_{ct'} \cdot \gamma_{c'h})$	21
$QI_{ct} = IA_t \cdot qinv_c$	22
Incomes and expenditures continued	
$QG_{ct} = ga_t \cdot qgov_c$	23
$YG_t = \sum_h th_h \cdot YH_{ht} + \sum_f tf_f \cdot YF_{ft} + \sum_c(tm_c \cdot pwm_c \cdot QM_{ct} \cdot X + tq_c \cdot PQ_{ct} \cdot QQ_{ct})$	24
Equilibrium conditions	
$qfs_{ft} = \sum_c QF_{fct}$	25
$QQ_{ct} = \sum_c' ca_{cc'} \cdot QN_{c't} + \sum_h QH_{cht} + QG_{ct} + QI_{ct} + QT_{ct}$	26
$\sum_c pwm_c \cdot QM_{ct} + \sum_f(1 - tf_f) \cdot rf_f \cdot YF_{ft} \cdot X_t^{-1} = \sum_c pwe_c \cdot QE_{ct} + \sum_h wh_h + cab_t$	27
$YG_t = \sum_c PQ_{ct} \cdot QG_{ct} + \sum_h gh_h \cdot pop_{ht} \cdot cpi + FS_t$	28
$\sum_h sh_h \cdot (1 - th_h) \cdot YH_{ht} + FS_t + cab_t \cdot X_t = \sum_c PQ_{ct} \cdot QI_{ct}$	29

Continued

Table A2
Model indices, variables, and parameters

Capital accumulation and allocation	
$AR_{ft} = \frac{YF_{ft}}{qfs_{ft}}$	30
$QK_{fct} \cdot \left(\sum_{c}' PQ_{c't} \cdot ci_{c'}\right) = \left(\frac{QF_{fct}}{qfs_{ft}} \cdot \frac{WF_{ft} \cdot WD_{fct}}{AR_{ft}}\right) \cdot \left(\sum_{c}' PQ_{c't} \cdot QI_{c't}\right)$	31
$QF_{fct+1} = QF_{fct} \cdot (1 - \upsilon) + QK_{fct}$	32
Land and labor supply, technical change, population growth, and other dynamic updates	
$qfs_{ft+1} = qfs_{ft} \cdot (1 + \varepsilon_f)$	33
$\alpha^p_{ct+1} = \alpha^p_{ct} \cdot (1 + \sigma_c)$	34
$pop_{ht+1} = pop_{ht} \cdot (1 + \varphi_h)$	35
$ga_{t+1} = ga_t \cdot (1 + \tau)$	36
$cab_{t+1} = cab_t \cdot (1 + \pi)$	37

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56, United Nations Food and Agriculture Organization, Rome, Italy.

Arndt, C., Benfica, R., Tarv, F., Thurlow, J., Uaiene, R., 2010. Biofuels, poverty, and growth: A computable general equilibrium analysis of Mozambique. Environ. Dev. Econ. 15, 81–105.

Arndt, C., Pauw, K., Thurlow, J., 2012. Biofuels and economic development: A computable general equilibrium analysis for Tanzania. Energ. Econ. 34(6), 1922–1930.

Berndes, G., 2002. Bioenergy and water: The implications of large-scale bioenergy production for water use and supply. Global Environ. Change. 12, 253–271.

Bernoux, M., Tinlot, M., Bockel, L., Branca, G., Gentien, A., 2011. EX-Ante Carbon-Balance Tool (EX-ACT): Technical Guidelines for Version 3, Easypol Module 101. Food and Agriculture Organization of the United Nations, Rome, Italy.

De Fraiture, C., Giordano, M., Liao, Y., 2008. Biofuels and implications for agricultural water use: Blue impacts of green energy. Water Policy. 10(S1), 67–81.

Diao, X., Thurlow, J., 2012. A recursive dynamic computable general equilibrium model. In: Diao, X., Thurlow, J., Benin, S., Fan, S. (Eds.), Strategies and Priorities for African Agriculture: Economywide Perspectives from Country Studies. International Food Policy Research Institute (IFPRI), Washington, DC.

Doorenbos, J., Kassam, A.H., 1979. Yield Response to Water. Irrigation and Drainage Paper 33, United Nations Food and Agriculture Organization, Rome, Italy.

Dunkelberg, E., Finkbeiner, M., Hirschl, B., 2013. Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions. Biomass Bioenerg. 71, 37–45.

EC (European Commission), 2010. Communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels. Offic. J. Euro. Union. C160, 8–16.

Ewing, M., Msangi, S., 2009. Biofuels production in developing countries: Assessing tradeoffs in welfare and food security. Environ. Sci. Policy. 12, 520–528.

Fargione, F., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238.

Gerbens-Leenes, P.W., Hoekstra, A.Y., 2009. The water footprint of sweeteners and bio-ethanol from sugar cane, sugar beet and maize. Value of Water Research Report Series No. 38, UNESCO-IHE Institute for Water Education, Delft, the Netherlands.

GOM (Government of Malawi), 2012. National Export Strategy (NES) 2013-2018, Volume 2. Annexes 1-5, Lilongwe, Malawi.

Herrmann, R., Grote, U., 2015. Large-scale agro-industrial investments and rural poverty: Evidence from sugarcane in Malawi. J. Afr. Econ. 24(5), 1–32.

IEA (International Energy Agency), 2015. World Energy Outlook 2015. Paris, France.

Kassam, A., Lutaladio, N., Friedrich, T., Kueneman, E., Salvatore, M., Bloise, M., Tschirley, J., 2012. Natural Resource Assessment for Crop and Land Suitability: An Application for Selected Bioenergy Crops in Southern Africa Region. Integrated Crop Management, Vol.14, FAO, Rome, Italy.

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Klein, N., Blok, K., Lam, L., Wong, L., Borkent, B., 2015. State and Trends of Carbon Pricing 2015 (September). The World Bank, Washington, DC, USA.

Mitchell, D., 2011. Biofuels in Africa: Opportunities, Prospects, and Challenges. The World Bank, Washington, DC, USA.

Msangi, S., Evans, M., 2013. Biofuels and developing economies: Is the timing right? Agric. Econ. 44(4–5), 501–510.

Negash, M., Swinnen, J.F.M., 2013. Biofuels and food security: Micro-evidence from Ethiopia. Energ. Policy. 61, 963–976.

NSO (National Statistical Office), 2012. Integrated Household Survey 2010/11. Lilongwe, Malawi.

NSO (National Statistical Office), 2014. Annual Economic Survey Report 2010-2011. Zomba, Malawi.

Pauw, K., Thurlow, J., Bachu, M., van Seventer, D., 2011. The economic costs of extreme weather events: A hydrometeorological CGE analysis for Malawi. Environ. Dev. Econ. 16, 177–198.

Pauw, K., Schuenemann, F., Thurlow, J., 2015. A 2010 Social Accounting Matrix for Malawi. International Food Policy Research Institute, Washington DC, USA.

Quintero, J.A., Cardona, C.A., Felix, E., Moncada, J., Sánchez, O.J., Gutiérrez, L.F., 2012. Techno-economic analysis of bioethanol production in Africa: Tanzania case. Energy 48(1), 442–454.

Rosegrant, M.W., Zhu, T., Msangi, S., Sulser, T., 2008. Global scenarios for biofuels: Impacts and implications. Rev. Agric. Econ. 30(3), 495–505.

Rosegrant, M.W., the IMPACT Development Team, 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy Research Institute (IFPRI), Washington, DC.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319(5867), 1238–1240.

SMEC, 2015. National Irrigation Master Plan and Investment Framework—Main Report for Republic of Malawi, Ministry of Water Development and Irrigation, Department of Irrigation. Lilongwe, Malawi.

Thurlow, J., Branca, G., Felix, E., Maltsoglou, I., Rincón, L.E., 2015. Producing biofuels in low-income countries: An integrated environmental and economic assessment for Tanzania. Enviro. Resour. Econ. 64(2),1–19.
Timilsina, G.R., Beghin, J.C., van der Mensbrugghe, D., Mevel, S., 2012. The impacts of biofuels targets on land-use change and food supply: A global CGE assessment. Agric. Econ. 43(3), 315–332.
Watson, H.K., 2011. Potential to expand sustainable bioenergy from sugarcane in southern Africa. Energ. Policy. 39(10), 5746–5750.
Zilberman, D., Hochman, G., Rajagopal, D., Sexton, S., Timilsina, G., 2013. The impact of biofuels on commodity food prices: Assessment of findings. Am. J. Agric. Econ. 95, 275–281.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website: