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Leveling the Field for Biofuels

Comparing the Economic and Environmental Impacts of Biofuel and Other Export Crops in Malawi

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ABSTRACT

Biofuel production can have conflicting impacts on economic growth, food and energy security, and natural resources. Understanding these trade-offs is crucial for designing policies that are consistent with the Sustainable Development Goals. This is particularly true in low-income countries, where the need to promote both energy and food security is most pressing. To this end, we develop an integrated modeling framework to simultaneously assess the economic and environmental impacts of producing biofuels in Malawi. We extend earlier studies by incorporating the effects of land use change on crop water use, and the opportunity costs of using scarce agricultural resources for biofuels rather than other export crops. We find that biofuel production is generally pro-poor and reduces food insecurity by raising household incomes. Irrigated outgrower schemes rather than estate farms lead to better economic outcomes, fewer greenhouse gas emissions, and similar crop water requirements. Nevertheless, Malawi must reduce emissions from its ethanol plants in order to access European markets. We also find that the economic and environmental impacts of biofuels are preferable to those of tobacco or soybeans. The European Union has raised the standards expected of biofuel producers, but it should "level the playing field" by applying similar standards to other export crops from developing countries.

Keywords: biofuels, economic growth, poverty, emissions, water use, Africa

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1. INTRODUCTION

Climate change and population and economic growth are placing unprecedented pressure on natural resources worldwide, demanding an improved understanding of the linkages between food, energy, and water systems. Biofuels are often cited as an example of how advances in one system may come at the expense of others. On the one hand, producing biofuels in low-income countries may reduce dependence on imported fossil fuels and help raise rural incomes (Msangi and Evans 2013). On the other hand, clearing new lands to cultivate biofuel crops generates greenhouse gas (GHG) emissions (Fargione et al. 2008), and diverting resources from food production could exacerbate food insecurity. The greater use of water resources for biofuels relative to fossil fuels is an additional concern, particularly in water-stressed countries (Berndes 2002).

Evidence on the effects of biofuel expansion is mixed. The spike in global food prices in the latter years of the 2000–2010 decade was partly attributed to global biofuel production (Rosegrant et al. 2008). Yet a recent review by Zilberman et al. (2013) finds no definite direction of impact, suggesting that the effect of biofuels on food prices depends on local contexts. Moreover, national studies find that if biofuel expansion stimulates economic growth, then higher incomes can more than offset higher food prices, leading to improved food security (Ewing and Msangi 2009; Arndt et al. 2010; Arndt, Pauw, and Thurlow 2012; Negash and Swinnen 2013). In regard to water, Berndes (2002) estimates that, given projected biofuel demand, evapotranspiration from bioenergy crops could eventually equal that of existing crops. Yet this and other studies conclude that enough water is available *globally* to expand biofuel production (De Fraiture, Giordano, and Liao 2008).

Concerns over food security and environmental impacts are constraining policy options in low-income countries. These countries often see biofuels as an export opportunity, and so require access to European Union (EU) markets, where preferential trade agreements enhance their competitiveness and where biofuel mandates ensure import demand. However, the EU's sustainability criteria impose strict conditions for accessing biofuel markets (EC 2010). By 2018, for instance, biofuels are required to generate 60 percent less GHG emissions than fossil fuels. Avoiding excessive water use and the displacement of food crops are also mentioned in the EU directive. These requirements will at least partly determine the feasibility of producing biofuels in low-income countries. Governments like Malawi's, who are considering investing public resources in biofuels production, need to know *in advance* how the EU's sustainability criteria will limit their options for promoting domestic biofuels industries.

Jointly evaluating economic and environmental impacts is analytically challenging. 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, for example, Searchinger et al. 2008; Timilsina et al. 2012). This overlooks the linkages and trade-offs between food, energy, and water systems and between new biofuel industries and other parts of the economy. We build on recent studies that use computable general equilibrium (CGE) models to estimate the impacts of biofuel production on economic growth and poverty (Arndt et al. 2010; Arndt, Pauw, and Thurlow 2012) and on GHG emissions (Thurlow et al. 2015). We extend this approach to include a more detailed treatment of agricultural resources for biofuel and existing crops, including estimates of crop water use and the water embodied within biofuels. Using a model of Malawi, we simulate sugarcane-ethanol production under different farming systems, including smallholder or estate farms on irrigated or rainfed lands. The CGE model is linked to crop models that estimate crop water requirements and to GHG inventory models that calculate GHG emissions from land use change. To our knowledge, this comprehensive approach comes closest to addressing the list of concerns in the EU's sustainability criteria.

One limitation of previous studies is that they used a "status quo" counterfactual when measuring biofuel impacts. These studies allow for the clearing of new lands for feedstock cultivation and new foreign investment in biofuel processing, and this generates some of the estimated positive growth effects from biofuels. However, if newly cleared lands are not used for biofuel feedstock, they could be used for other crops, such as tobacco or cotton. A more appropriate counterfactual would consider alternative uses for newly cleared lands rather than assume no new lands are cleared in the absence of biofuels. This is the approach taken in our analysis. The choice of counterfactual has important policy implications. Currently the EU's sustainability criteria apply only to biofuels even though expanding other export crops in low-income countries might also displace food production, generate GHG emissions, and use water resources. The EU has raised the bar for biofuels production in low-income countries. By comparing biofuels to other export crops, our analysis levels the playing field for evaluating economic and environmental impacts.

The remainder of this paper 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 findings. We conclude by summarizing our findings and discussing their implications for biofuel policy in Malawi, the EU, and elsewhere.

2. BIOFUELS IN MALAWI

Food, Energy, and Water

Malawi provides an interesting case study for examining the linkages between biofuels and food security. Agriculture is responsible for one-third of Malawi's gross domestic product (GDP) and four-fifths of employment. Most farmers are poor smallholders growing food crops for subsistence. Many smallholders also grow burley tobacco, which is Malawi's main export. A few large estate farms grow mainly maize and sugarcane. Due to a general decline in tobacco demand worldwide, Malawi is searching for alternative export crops, particularly ones that might involve smallholders. Biofuels is one option identified in the government's new export strategy (MIT 2012). Malawi imports all of its fossil fuels, and so biofuels would have the added benefit of reducing the country's severe foreign exchange constraints.

There are strong linkages between Malawi's agricultural, energy, and water systems. One-fourth of Malawi is covered by Lake Malawi, which is Africa's third largest freshwater lake. Irrigation potential is high, and water scarcity should be a minor concern. Yet most smallholders practice rainfed farming and the country experiences frequent droughts. The annual economic cost of weather variability is estimated at 1.7 percent of national GDP (Pauw et al. 2011). Irrigation infrastructure is unaffordable for most smallholders, and only 4 percent of cropland is irrigated (DOI 2015). Most of Malawi's electricity supply is from hydropower, and reductions in dam water levels can lead to electricity shortages.

There is competition over land resources in Malawi, particularly in the central and southern regions. Malawi is the second most densely populated country in Africa, and the average smallholder cultivates less than one hectare of land. Agricultural land expansion is severely constrained, and so any expansion of biofuel crops is likely to lead to at least some displacement of existing crops on smallholder lands.

Sugarcane-Ethanol

A biofuel export strategy in Malawi would start from an established base. Malawi has produced sugarcane since the 1960s. Two large estate farms currently grow about 80 percent of the feedstock, and the rest is produced via smallholder outgrower schemes. Malawian sugarcane is almost entirely irrigated and, because of favorable agroclimatic conditions, achieves yields of about 100 metric tons per hectare, which is high by international standards. The sugar industry is the second largest formal sector employer in Malawi and provides permanent jobs for more than 15,000 people.

Ethanol production from sugarcane molasses started in the late 1980s as a means of reducing the foreign exchange burden of importing fossil fuels (Thomas and Kwong 2001). The government introduced a petrol-ethanol blending mandate of 10–20 percent, and in 2010, 18 million liters of ethanol were produced, compared with 360 million liters of petroleum that were imported. The country is still far from meeting its own blending mandate. Ethanol prices are currently pegged to the price of imported petroleum, making locally blended petrol-ethanol equally as expensive as imported petroleum.

Malawi could export biofuels to both the EU and the Southern African Development Community (SADC). Malawi has preferential access to EU markets through the Everything but Arms Initiative, and the country is part of SADC's Free Trade Area. Foreign investors have shown interest in producing biofuels in Malawi (MIT 2012). One important constraint, however, is the availability of lands suitable for growing sugarcane. Kassam et al. (2012) estimate that 14,000 hectares of uncultivated land is available for rainfed sugarcane. Malawi's irrigation investment plan would increase the amount of suitable lands to around 50,000 hectares (DOI 2015). Realizing Malawi's full irrigation potential, which Watson (2011) estimates at 300,000 hectares, would require substantial infrastructure investments. Land availability is clearly a binding constraint for biofuel expansion in Malawi.

Ethanol Production Technologies

Malawi's new export strategy plans to expand sugarcane production by an additional 75,000 hectares (MIT 2012). This is about 2 percent of the total cropland in Malawi and so is unlikely to have major economywide implications. We therefore simulate a more ambitious biofuel export strategy to gauge potential impacts. Estimated outcomes in our analysis are roughly proportional to the scale of biofuel expansion.

Three broad biofuel options are available to Malawi based on existing sugarcane production technologies. Table 2.1 shows the technologies used to produce 1 billion liters of ethanol per year, assuming a conversion ratio of 70 liters of ethanol per metric ton of feedstock. One option is to continue growing sugarcane on large estate farms that use irrigated farming system and achieve high yields of 108 tons per hectare. This option requires 132,000 hectares of feedstock land. The alternative is to use smallholder outgrower schemes, which may be irrigated or rainfed. Irrigated smallholders achieve yields of 99 tons per hectare, which is close to that of estate farms and so has similar cropland requirements (144,000 hectares). Smallholders growing rainfed sugarcane achieve much lower yields of 42 tons per hectare and therefore require 340,000 hectares of land to produce the targeted ethanol production levels. Given Malawi's land constraints, the choice of technology will influence the extent of both land clearing and crop displacement.

Table 2.1 Sugarcane-ethanol production technologies

Variable	Input requirements per billion liters of sugarcane-based ethanol		
	Irrigated estates	Irrigated outgrowers	Rainfed outgrowers
Liquid yield (liter/mt)	70.0	70.0	70.0
Feedstock required (1000 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/ million liters)	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/million liters)	23.6	12.1	10.0

Source: Authors' estimates using farm budget survey data (Herrmann and Grote 2015) and processing cost estimates (Quintero et al. 2010).
Notes: mt = metric tons; ha = hectares.

The production technologies in Table 2.1 are derived from various sources. Information on smallholder production is taken from a recent survey of sugarcane outgrowers (Herrmann and Grote 2015). Estate technologies are taken from Malawi's Annual Economic Survey, which provides detailed input cost information (NSO 2014). Ethanol processing costs are from a study of large-scale processing plants in Tanzania by Quintero et al. (2012), updated to reflect Malawian feedstock and labor costs. Malawi currently produces ethanol from molasses at two low-capacity processing plants. We assume that new plants with better technology would be required to realize the new export strategy. We assume the processing technology is used regardless of which farming system produces the sugarcane.

As shown in Table 2.1, large-scale ethanol processing is not particularly labor intensive. Most jobs created in the biofuel industry are in growing feedstock. Estate farms are less labor intensive than smallholder schemes, and so job creation (and wages) will differ depending on the choice of farming system.

In the next section we develop an integrated modeling framework that incorporates the different biofuel technology options and evaluates how the choice of technology influences the economic and environmental impacts of biofuel production.

3. MEASURING ECONOMIC AND ENVIRONMENTAL IMPACTS

Economywide models are ideal tools for evaluating the impacts of large-scale interventions in developing countries such as Malawi. These models capture the complete flow of incomes within an economy and incorporate all consumption and production linkages between economic actors and markets. We complement the CGE model with two natural resource models that measure environmental impacts: a crop model used to measure crop water use, and a model called Ex-ante Carbon-Balance Tool (EX-ACT) that measures GHG emissions from land use change.

Economywide Model

We use the recursive dynamic CGE model described in Diao and Thurlow (2012) to measure the economic impacts of producing biofuels in Malawi. The model consists of behavioral and structural equations. The former governs the decision making of economic agents; the latter maintains consistency between the incomes and expenditures of individual agents and within the macroeconomy.[1] Producers and consumers maximize profits and utility, respectively, and interact with one another in factor and product markets. Production in each sector is determined by constant elasticity of substitution (CES) functions that allow substitution between factors based on relative factor price changes. Intermediate input use is determined by fixed input-output coefficients in Leontief functions. Commodities can be traded with the rest of the world, with domestic, export, and import quantities determined by relative prices (inclusive of relevant taxes and transaction costs). Substitution between imports and domestic goods is governed by a CES function, whereas the decision to export is based on a constant elasticity of transformation function. World prices are fixed under a small country assumption.

The parameters of the model are assigned values derived from a social accounting matrix (SAM) (see Pauw, Schuenemann, and Thurlow 2015). The model contains 58 sectors with their own production technologies and functions. We introduce new biofuel sectors that replicate the sugarcane and ethanol production technologies shown in Table 2.1. Initial output in these sectors is effectively zero. In our simulations, we exogenously expand the level of output in the biofuel sectors to meet ethanol production targets. As the biofuel sectors grow, they draw in land, labor, and other inputs, and by doing so, influence factor prices and production levels in other sectors, including food and existing export crops. The model distinguishes between six types of labor: three education levels separated across rural and urban areas. Agricultural land is divided into four groups: small, medium, and large smallholder plots and large-scale estates. Given land and labor constraints in Malawi, all factors are assumed to be fully employed, and capital is also sector specific.

The model captures the distributional impacts of biofuels by disaggregating households in Malawi into representative groups based on their location (rural or urban), farm size (small, medium, or large), and per capita consumption quintiles. Households choose between producing goods for their own consumption and purchasing goods from markets. Households are the main owners of the factors of production, and their wages, rents, and profits are used to consume goods, pay taxes, and save. Consumption levels are determined by a linear expenditure system (LES) of demand, with income elasticities estimated using Malawi's 2010/2011 Integrated Household Survey (IHS3) (NSO 2012). A microsimulation module estimates changes in poverty rates following the approach in Arndt, Pauw, and Thurlow (2012). Households in the survey are mapped to their representative household groups in the CGE model. The module transfers proportional real consumption changes from the CGE model down to the households in the survey and then recalculates each household's consumption levels and poverty status (using the official fixed poverty line).

The model maintains macroeconomic consistency by using three "closure rules": First, foreign capital inflows are assumed to be fixed (beyond what is needed to expand biofuels production), and a flexible exchange rate adjusts to maintain the supply and demand of foreign exchange. Second,

[1] The model is calibrated to a 2010 social accounting matrix (SAM) (see Pauw, Schuenemann, and Thurlow 2015).

investment is savings driven, meaning that households' marginal propensities to save are fixed, and therefore rising incomes lead to higher levels of savings and investment. Finally, the government earns tax revenues based on fixed tax rates. These revenues finance fixed levels of recurrent spending, leaving the recurrent deficit to adjust to maintain fiscal balance. The domestic price index is the model's numeraire.

We run the model over a 10- year period.2 Between periods we update parameters based on long-term trends to reflect changes in factor supplies and productivity, household population growth, government spending, and foreign capital inflows. Capital stocks within each sector are updated each year to reflect depreciation and investments from the previous period. Sectors with above-average profits receive a larger share of new capital stocks than their share of installed capital in the previous period.

Simulating Biofuels Production

We initially assume that production levels using the *new* biofuel technologies are fixed at effectively zero. We then expand the amount of foreign capital invested in new ethanol processing plants, causing output to expand and drawing in factors and intermediate inputs, including sugarcane feedstock. Ethanol production in each scenario is gradually increased until it reaches 1 billion liters per year by the end of the 10-year simulation period. The capital needed to produce biofuels is assumed to come from abroad, and all profits are repatriated. To simplify the modeling, we assume that all additional ethanol produced in Malawi is exported. In reality, some ethanol may be used domestically to meet the government's blending mandate. However, since ethanol and petroleum are near-perfect substitutes, little difference exists from a macro-accounting perspective between (1) exporting ethanol and using the foreign exchange earning to pay for imported fossil fuels and (2) reducing fuel imports by redirecting ethanol to domestic markets, and forgoing additional foreign exchange earnings.

We run two sets of scenarios for each of the production technologies shown in Table 2.1. In the first set of scenarios we assume that 132,000 hectares of new land are cleared and used to grow biofuel feedstock. This is exactly the amount of land needed by estate farms to produce the targeted level of ethanol production. As such, there is no need to displace existing crops in this scenario. The smallholder scenarios require more than 132,000 hectares of land, meaning that some crop displacement will be needed. Binding land constraints ensure that we do not bias our results in favor of more land-intensive smallholder production options.

In the second set of scenarios, we adhere to the land suitability study by Kassam et al. (2012) by assuming that only 14,000 hectares of new suitable land can be cleared for sugarcane. Competition over land resources and the extent of crop displacement become more pronounced. Since total land and labor supplies are fixed, some sectors will lose depending on their relative factor intensities. Table 3.1 shows the technologies of existing crops and new sugarcane in Malawi. On average, existing crops generate lower GDP per hectare and per worker than the new sugarcane feedstock crops. Reallocating resources to biofuel crops should therefore lead to an increase in average value-added per hectare and worker. These differences in technology between crops will determine the growth and displacement effects in the model's simulations. The table also reports crop water use, which is calculated using crop models.

[2] The model's base year is 2010, which is the year used to construct the social accounting matrix.

Table 3.1 Biofuel and existing crop production technologies, 2010

Variable	Production		Water use		Labor	Value-added or GDP per unit of input		
	Area (1000mt)	Yield (mt/ha)	Total (1000m^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: Authors' estimates using production data from FAOSTAT; employment data from IHS3 (NSO 2012); value-added data from the 2010 social accounting matrix (Pauw, Schuenemann, and Thurlow 2015); and estimated water use from the process-based crop models (see Section 3).

Notes: mt = metric tons; ha = hectares; m^3 =cubic meters.

Estimating Crop Water Use

Sugarcane is a water-intensive crop (relative to other crops in Malawi); therefore, producing biofuels should increase the consumptive use of water through the evapotranspiration of plants. Irrigation further increases water consumption because some water is lost during transportation and through inefficient irrigation management. Even in the most efficient schemes, only 50–60 percent of irrigated water is actually used by crops (Brouwer, Prins, and Heilbloem 1989). To measure actual crop water use, we develop a crop model tailored to the specific water needs of crops in Malawi. The model follows the Food and Agriculture Organization of the United Nations' (FAO's) "yield response to water" approach, which assumes a linear relationship between relative yield declines and relative water deficits (Doorenbos and Kassam 1979). Water deficits are defined by the ratio of actual to potential crop evapotranspiration.

Potential evapotranspiration is the amount of water that a plant would use if, given climatic circumstances, enough water is available. Reference evapotranspiration for a hypothetical grass crop was computed using the Penman–Monteith equation and climatological data from 20 Malawian weather stations for the period 1983–2005. Potential evapotranspiration for each crop was then calculated by multiplying the reference evapotranspiration value by a coefficient that captures crops' unique physical and physiological properties. Coefficients for Malawi were taken from Allen et al. (1998) and Rosegrant et al. (2012).

Actual evapotranspiration for rainfed and irrigated crops was calculated using daily soil–water balances derived using precipitation data from weather stations and soil data from the Africa Soil Profiles Database. The use of irrigation water is computed so as to reduce the frequency of irrigation, while also ensuring that crops do not suffer water stress. Note that the calculated amount of irrigation water is the *net* irrigation requirement. The *gross* irrigation requirement may be much higher due to water lost during the irrigation process.

Based on the above calculations, we estimated the potential evapotranspiration of crops during an average weather year in Malawi. This average yield is compared with the yield used in the CGE model to determine actual evapotranspiration (that is, water use) using the FAO's equation. Table 3.1 shows how the sugarcane feedstock crops are far more water intensive than existing crops. Irrigated estate sugarcane, for example, consumes four times more water per hectare than existing crops. We use these numbers to calculate how the water intensity of agriculture in Malawi increases in the biofuel production scenarios.

It should be noted that our crop models estimate *approximate* water use, since potential and actual evapotranspiration depend on many complex climatic conditions. During droughts, for example, potential evapotranspiration is extremely high, because low humidity, little cloud cover, and high temperatures raise soil evaporation (Hanson 1991). Actual evapotranspiration (without irrigation) may be unusually low, since transpiration of crops decreases in an attempt to save water. In the FAO equation, actual evapotranspiration increases linearly and proportionately to potential evapotranspiration and so gives the wrong estimate during drought events. Thus, even though our time series includes climate data during five serious countrywide drought seasons and five floods occurring mainly in the Southern Region of Malawi, these events cannot be sufficiently reflected by our simple crop model.

Given the difficulties in measuring crop water use under weather variability, we focus on crop water requirements during an *average* year in Malawi. Anthropogenic climate change could alter weather variability and increase the number of extreme weather events. In the case of floods, crops like sugarcane could be lost, making crop water use a minor concern. During droughts, the water intensity of rainfed agriculture in Malawi is lower than average, but water use for irrigated crops like sugarcane is higher. Therefore, if climate change leads to more droughts, then our results provide a lower bound for the effect of increased ethanol production on the water intensity of agriculture in Malawi.

Measuring Greenhouse Gas Emissions

Land use change in our CGE model affects both crop water requirements and GHG emissions. The EU's sustainability criteria will restrict total permissible GHG emissions from biofuel production to 40 percent of fossil fuel emissions by 2018. The default average life cycle GHG emission of petroleum is 2.92 kilograms of carbon dioxide equivalents per liter (kgCO_2eq/l). Therefore, if Malawi wants to export to EU markets, the maximum permissible emissions from ethanol production is 1.17 kgCO_2eq/l. Dunkelberg, Finkbeiner, and Hirschl (2014) estimate emissions from current ethanol-molasses production in Malawi at 4.04 kgCO_2eq/l. Most of these emissions are from unsustainable handling of waste products and coal heating in ethanol processing. The authors estimate that if energy is derived from waste products as a coproduct, which is similar to the assumption in Quintero et al. (2012), then emissions fall to 2.05 kgCO_2eq/l, of which 1.15 kgCO_2eq/l is from ethanol processing. We use these estimated emissions from ethanol processing in our scenarios, and then add to this the emissions from clearing lands and producing feedstock.

EX-ACT 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 (Bernoux et al. 2011). The measurement of emissions follows the approach in IPCC (2006). Soil sequestration values for Malawi come from the World Bank's Soil Carbon Sequestration Geodatabase. The model is calibrated to tropical conditions and to soil types that are prevalent in Malawi's Southern and Central Regions—the likely locations for growing new sugarcane.

Land clearing for sugarcane in the CGE model leads to direct land use change and the displacement of other crops.[3] We assume that grasslands are cleared because any deforestation generates emissions that far exceed EU thresholds. Forests were also excluded from Malawi's land suitability assessments. 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, the net emissions depend both on the inputs used to grow each crop and on the soil organic carbon sequestration (SOC) potential of crops. We use two reference crops when estimating changes in net emissions. For displaced food crops, we use the SOC value of maize (0.617 tons of carbon per hectare per year or tC/ha/yr), as this is Malawi's main staple crop. For export crops, we use the SOC value of soybeans (0.839 tC/ha/yr) because this is one of the most affected crops in our simulations. Irrigated sugarcane is more input intensive and therefore generates higher emissions than rainfed sugarcane. However, sugarcane itself is a carbon sink relative to the reference crops, with a SOC of 1.220 tC/ha/yr. This reflects the heavier biomass of sugarcane.

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

4. RESULTS

Baseline Scenario

The CGE model's baseline scenario tracks recent trends in population and economic growth in Malawi. Labor and land supplies grow at 2.0 and 1.7 percent per year, respectively, and total factor productivity grows at 2.7 percent per year. Together this generates annual GDP growth of 4.7 percent (see Table 4.1), and this growth is fairly evenly distributed across sectors. Note that the baseline scenario is of only marginal interest for our analysis, as it merely provides a reference for measuring the impacts of expanding biofuel production. In discussing the impacts of biofuel crops, we compare biofuels first to this status quo baseline scenario (as in previous studies) and then later to alternative scenarios that allow for the expansion of other export crops.

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 4.1 reports final-year deviations from baseline for the Irrigated Estate scenario. This scenario shows no direct crop displacement because newly cleared lands exactly equal the amount of land required to grow feedstock on estate farms (see Table 2.1). However, it does show indirect land use change. Lands are reallocated from existing export crops (such as tobacco) to food crops (such as maize). This is driven by biofuel exports, which grow rapidly and cause the real exchange rate to appreciate, thereby reducing the competitiveness of non-biofuel 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 3.1), 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 non-biofuel export crops—we find that biofuels production in Malawi might eventually lead to improved food availability.

Table 4.2 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 3.1), causing the overall labor share of agriculture 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 (for example, 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 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.

Table 4.1 Production and price impacts

Variable	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	1.8	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 non-biofuels	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 indexes (%)								
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 cropland (1000ha)	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.
Notes: Biofuels processing grows from a zero base, and so growth is infinite. ha = hectares.

Table 4.2 Labor and household impacts

Variable	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.

Notes: 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.

Ultimately, national GDP is 2 percent higher in the Irrigated Estate scenario than in the baseline. This positive growth effect from biofuels is driven by (1) an increase in the level of productive resources in the economy, that is, from newly cleared lands and additional foreign capital; (2) higher value-added per worker and per hectare of cropland in the biofuel sectors; and (3) 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 biofuels 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 3.1). 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.

Using Outgrower Schemes

Smallholders achieve lower yields and require more land to meet the biofuel production target (see Table 2.1). The fourth column of Table 4.1 reports results for the Irrigated Outgrower scenario. Producing sugarcane feedstock now requires 144,000 hectares, but we still allow only 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 in the Irrigated Estate scenario, because more of the on-farm profits from growing sugarcane via outgrower schemes remain with smallholders rather than being repatriated to foreign investors. Higher smallholder incomes also generate greater demand for products that smallholders consume more 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 2.1), and therefore, using outgrower schemes increases labor requirements in agriculture. Overall, the employment share in agriculture rises in the Irrigated Outgrower scenario and is matched by higher agricultural GDP growth (see Table 4.2). 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. Rural rather than urban households now experience the largest gains in welfare and poverty reduction.

Relying on Rainfed Production

In the Irrigated Outgrower scenario 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 2.1). 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 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 4.1. 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. A positive effect on national GDP is still seen, 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 3.1). 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 3.1), and so reallocating land leads to a higher average labor intensity for agriculture as a whole. The share of employment in agriculture 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 outcomes.

Environmental Impacts and Trade-offs

Table 4.3 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 irrigation efficiency rate of 50 percent, irrigated smallholder cultivation uses almost twice as much water as rainfed sugarcane (3,387 versus 1,720 liters). Rainfed agriculture is most efficient in its water use, but it achieves lower yields and uses more land.

Table 4.3 Emissions and water use

	Biofuel scenarios with land expansion			Biofuel scenarios with land constraints		
Variable	**Irrigated estates**	**Irrigated outgrowers**	**Rainfed outgrowers**	**Irrigated estates**	**Irrigated outgrowers**	**Rainfed outgrowers**
Greenhouse gas 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 greenhouse gas 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 (million m^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.

Notes: Greenhouse gas emissions are measured by tons of CO_2 equivalent per liter of ethanol per year. kgCO_2eq/l/yr = kilograms of carbon dioxide equivalent per liter per year; m^3 = cubic meters.

Our estimated water requirements are fairly high. Gerbens-Leenes and Hoekstra (2009) estimated that Brazil, as the world's largest ethanol producer, uses 2,500 liters of water per liter of ethanol. These authors included polluted gray 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 billion liters of ethanol. This appears to be small relative to the 8.4 trillion 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 4.3 reports changes in total 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 3.1), thus driving up total evapotranspiration. Overall, sugarcane-ethanol expansion in our simulations increases the water intensity of Malawian agriculture by almost 10 percent, irrespective of which biofuel production technology is used, although land area increases by only 2.6 percent.

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 4.3 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, for example, from 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 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, especially if sugarcane is grown on irrigated lands with inputs that directly or indirectly use fossil fuels. Even after 20 years, emissions in the Rainfed Outgrower scenario are still 1.47 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, Finkbeiner, and Hirschl (2014) find that if ethanol plants in Malawi switch from coal to energy produced by crop residues, then 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.

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 land constraints and so exaggerates 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 more conservative than DOI (2015) or Watson (2011). The final three columns in Table 4.1 report results for biofuel production under land constraints. Each scenario should be compared with 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 greater displacement of existing crops, particularly for export crops. However, 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 the higher land productivity of sugarcane 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 the share of agricultural employment does not increase by as much (see Table 4.2). 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 trade-offs between production technologies are starker with stricter land constraints.

Emissions per liter of ethanol are much lower when there is less land clearing (see Table 4.3). 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 (that is, if we deduct displaced crop water use), then additional water use resulting from producing biofuels is 20 percent lower than in the previous scenarios (for example, 109/136 = 0.80 for the Irrigated Outgrower scenarios). Yet even with this more lenient measurement, water use of ethanol 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.

Biofuels versus Other Export Crops

So far we have followed the approach of previous studies by comparing expanded biofuel production to a status quo baseline. Yet Malawi's export strategy (MIT 2012) suggests that if croplands are not used to grow sugarcane for ethanol, they might be used to grow other export crops. A more appropriate counterfactual would consider these opportunity costs. We consider two alternative export crops: tobacco and soybeans. Tobacco is a well-established smallholder crop with strong downstream linkages to agroprocessing. Soybean is a new crop identified in the export strategy. In our new counterfactuals, we assume that additional tobacco and soybean production uses technologies that already exist in Malawi (see Table 3.1). However, as with biofuels, increased tobacco and soybean production is financed by foreign capital, and all profits are repatriated. We simulate a 144,000 hectare expansion in cropland devoted to outgrower tobacco or soybeans and allow for 14,000 hectares of newly cleared lands. Our new counterfactuals can therefore be compared directly with the Irrigated Outgrower scenario.

Table 4.4 reports results for the Tobacco and Soybean scenarios alongside results from the Irrigated Outgrower scenario. Agricultural exports increase in all three 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 3.1), and so expanding their cropland area draws labor away from food crops. Share of total agricultural employment in the Tobacco and Soybeans scenarios increases by 5.6 and 4.6 percentage points, respectively, compared with a 1 percentage point increase in the Irrigated Outgrower scenario. The results demonstrate how both land and labor displacement are important in determining impacts on food production.

Table 4.4 Comparing biofuels to tobacco and soybean

Variable	Deviation from final year baseline value (%)		
	Irrigated sugarcane outgrowers	Rainfed tobacco outgrowers	Rainfed soybean outgrowers
Total cropland (1000ha)	5,024	5,024	5,024
of which cleared lands	14	14	14
Total GDP growth (%)	1.4	0.4	0.0
Agriculture	2.1	1.2	0.5
Food crops	0.9	–0.7	–1.3
Export crops	17.5	17.1	12.2
Industry	–0.5	0.7	0.7
Services	1.7	–0.2	–0.5
Change in price indexes (%)			
Real exchange rate	–3.2	–1.0	–0.3
Real food prices	–0.1	0.5	0.5
Household welfare (%)	1.0	0.2	–0.1
Farm households	1.1	0.4	0.1
Nonfarm households	0.7	–0.4	–0.4
Poverty headcount rate (%)	–1.4	–1.1	–0.4
Farm households	–1.4	–1.2	–0.4
Nonfarm households	0.0	0.3	0.3
Total crop water use (million m^3)	1,407	1,333	1,377
Emissions from feedstock production (tCO_2eq/yr)			
Per ha after 10 years	1.6	1.7	0.7
Per additional US$ GDP	1.6	6.4	34.0

Source: Results from the Malawi CGE and microsimulation models.
Notes: 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. ha = hectares; m^3 = cubic meters; tCO_2eq/yr = tons of carbon dioxide equivalent per year.

Tobacco and soybeans generate less value-added per hectare than sugarcane, and so agricultural GDP gains are smaller. All three crops create downstream jobs, but tobacco and soybean processing are more labor intensive. The rising labor intensity of agriculture and the creation of more industrial jobs means that fewer workers migrate to the service sectors. Total GDP is unchanged in the Soybeans scenario because of this crop's low land productivity. Agricultural gains are exactly offset by nonagricultural losses. Tobacco production expands total GDP, but these gains are smaller than in the sugarcane 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 considerably larger in the Irrigated Outgrower scenario. Biofuels production therefore leads to better economic outcomes than production of the two alternative export crops.

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. Sugarcane-ethanol is, however, even more water intensive than tobacco or soybeans. This justifies some of the concerns raised about the pressure that producing biofuels places on water resources. That being said, the emissions per hectare of sugarcane is lower than the emissions from tobacco. The emissions of sugarcane per dollar of crop GDP are lower than those of tobacco or soybeans.[4] All three crops generate net positive emissions. However, the greater biomass of sugarcane means that it is a larger carbon sink than the two alternative crops, even though sugarcane is irrigated and uses more fertilizers.

[4] 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.

5. CONCLUSION

We used an integrated modeling framework to jointly assess the economic and environmental effects of producing 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. Each farming system has clear trade-offs. Nevertheless, we conclude that irrigated smallholder outgrower schemes operating on existing croplands are 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. 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. Our study suggests that there should also be a level playing field that applies similar standards to alternative exports from low-income countries like Malawi.

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