Sustainability of ethanol production in Uganda

Abstract

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This study uses a recursive dynamic computable general equilibrium model to evaluate the socio-economic and environmental sustainability of maize, cassava, and sugarcane ethanol in Uganda. Socio-economic sustainability is assessed considering the source of capital, and the findings reveal more growth effects under local capital than foreign capital. Household incomes rise faster under the former, and so does real GDP. The environmental dimension is evaluated with respect to ethanol's GHG emissions reduction relative to gasoline. Without land-use change, all the ethanol types achieve a substantial reduction in emissions compared to gasoline. Conversion of grassland to feedstock farming releases more emissions, taking 15 years for maize ethanol, 13 for cassava ethanol, and 5 for sugarcane ethanol to break even with gasoline. Ethanol from sugarcane on deforested land would break even within 15 years. It is, however, found that all ethanol has a payback period beyond 15 years. Overall, sugarcane ethanol could contribute to climate change mitigation because of its emissions saving. Maize and cassava ethanol underperform mainly because of the low crop yields. From the findings, prioritizing local investors would avoid profit repatriation and attenuate some adverse effects. Biofuels policies should be pursued in concert with the promotion of other low-carbon energy sources and the improvement of crop yields. High yields will benefit not only ethanol producers but also the poor landless as food prices fall and labor demand rises.

Keywords: ethanol, sustainability, environmental, land-use-change, emissions, CGE

1.0 Introduction

The production of ethanol, a biofuel, is essentially related to the three dimensions of sustainability. From the social and economic perspective, aside from promoting self-sufficiency and energy security, ethanol contributes to well-being through employment and the creation of markets for agricultural commodities, enhancing household income (Nakamya & Romstad, 2020; Hartley, van Seventer, Tostão, & Arndt, 2019). In this regard, it promotes socio-economic equity as societies become economically independent. However, this may be achieved at the expense of extensive use of scarce resources such as land

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(Paschalidou, Tsatiris, & Kitikidou, 2016). Consequently, soil quality may deteriorate, affecting both the present and future generations.

Moreover, the deployment of biofuels also hinges on the investment level in the biofuels sector, which is driven by capital availability. Capital is locally, or foreign-sourced, such as foreign direct investment (FDI), and the source may influence the socio-economic outcomes. Although local capital avoids profit repatriation, it is scarce in developing countries. Thus, mobilizing it to fund ethanol projects may cause competition and crowd out other sectors. FDI is known to provide financial, technological, and other resources to mainly developing countries whose sectors would have otherwise found it difficult to take off. Nonetheless, the FDI literature has revealed that the benefits are not guaranteed, as some adverse effects may occur (Agosin & Machado, 2005; Herzer, 2012). For example, Reis (2001) shows that FDI may decrease national welfare effects because of profit repatriation. The adverse effects could even be amplified if FDI competes with local firms for scarce resources, such as land and skilled labor.

From an environmental point of view, sustainable biofuels systems contribute to keeping natural resources in balance. For example, in Uganda, ethanol could substitute gasoline and slow the country's oil reserves' extraction rate. Despite a number of negative reviews, ethanol has proven effective in reducing emissions compared to gasoline (see EPA, 2010; Lewandrowski et al., 2019; Elshout et al., 2019; Unnasch & Parida, 2021). Therefore, the displacement of fossil fuels and carbon sequestration during feedstock growth promotes a low-carbon economy. To some extent, this improves air quality and contributes to mitigating environmental degradation and climate change. While this is true, the increased demand for land to produce feedstocks could cause both direct and indirect land-use change (LUC) emissions[1] (Fargione et al., 2008; Searchinger et al., 2008; Acheampong, Ertem, Kappler, & Neubauer, 2017). In addition, changes in farming practices, increases in fertilizers and other inputs application, excessive water use, and impacts on biodiversity may also occur.

Biofuels programs and policies have been predominantly aligned with the three sustainability goals. For instance, Brazil's biodiesel program provided tax subsidies to producers who purchased a minimum amount of feedstocks from family-owned farms. The producers were supposed to have agreements with the farmers regarding the pricing and delivery of raw materials. They also provided technical assistance (Rodrigues & Accarini, 2016). Such a policy is inclusive and tries to incorporate all three sustainability pillars.

[1] Land use change may have an increasing or reducing effect on the soil organic carbon content depending on the type of crops. Aside from this, crops also sequester carbon dioxide from the atmosphere.

Additionally, the certification standards and emissions thresholds in some jurisdictions ensure that biofuels meet a minimum level of emissions reduction. For example, the US 2007 Renewable Fuel Standard (RFS2) requires biofuels from refineries constructed after its enactment to achieve at least 20 percent life cycle GHG emissions reduction relative to fossil fuels. This threshold was set at 50 and 60 percent for the advanced and cellulosic biofuels, respectively [2] (Environmental Protection Agency (EPA), 2010; Schnepf & Yacobucci, 2010).

There is a considerable body of research on the socio-economic aspects of biofuels (Huang, Yang, Msangi, Rozelle, & Weersink, 2012; Portale, 2012; Campbell, Anderson, & Luckert, 2016; Zilberman, Hochman, Rajagopal, Sexton, & Timilsina, 2013; Gebreegziabher et al., 2018; Hartley et al., 2019; Nakamya & Romstad, 2020). This research also analyzes the impacts of biofuels on other sectors and related economic activities, particularly the analyses based on a macroeconomic modeling approach. However, it does not capture the specific activities along the biofuels supply chain.

On the other hand, life cycle analyses (LCA) have been used to quantify the environmental impacts of products, and in this case, biofuels. Some have focused on energy and carbon footprints (Seabra, Macedo, Chum, Faroni, & Sarto, 2011; Wang, Han, Dunn, Cai & Elgowainy, 2012; EPA, 2010; Lewandrowski et al., 2019). Some LCAs are extended to include the water footprint (Wu, Mintz, Wang, & Arora, 2009; Gheewala et al., 2013; Kaenchan & Gheewala, 2017; Mekonnen et al., 2018; Ghani, Silalertruksa, & Gheewala, 2019; Demafelis et al., 2020).

The interconnection of biofuels with other sectors and the trade-offs involved require a framework that considers all the sustainability pillars to inform sound decision making (Nazari, Mazutti, Basso, Colla, and Brandli (2020). A few studies have taken this approach (see Obidzinski, Andriani, Komarudin, & Andrianto, 2012; Thurlow, Branca, Felix, Maltsoglou, & Rincón, 2016; Schuenemann, Thurlow& Zeller, 2017). However, such studies are still scarce, particularly those examining the implications of capital sources on biofuels development.

Moreover, the above and other LCA literature review presents contextual findings, greatly influenced by local factors, types of feedstocks, the data used, system boundaries, and parametric assumptions (Jeswani, Chilvers, & Azapagic, 2020; Mayer, Brondani, Carrillo, Hoffmann & Lora, 2020). Similarly, socio-economic outcomes are also driven by specific factors. Therefore, this study extends the above literature

[2] Advanced ethanol in this case is non-corn ethanol from feedstocks such as wheat, sorghum, and cornstalks and cobs. Cellulosic ethanol is derived from cellulose, hemicellulose, and lignin (Schnepf & Yacobucci, 2010).

to explore the sustainability of ethanol in Uganda's context by addressing the following research questions: What influence may local and foreign capital have on the socio-economic benefits of ethanol production? To what extent will ethanol reduce GHG emissions relative to gasoline in Uganda's context?

Since the Renewable Energy Policy (2007), the Ugandan government has made efforts to promote the production and use of renewable energy, including biofuels. For example, the biofuels Act of 2018 and the Biofuels General Regulations draft intended to enable an initial blending of 5 percent for ethanol and biodiesel [3]. Moreover, a fuel blend of up to 20 percent is one of the Biomass Resource Management Investment Priorities for 2020/21, under the Ministry of Energy and Mineral Development (MEMD). It is also anticipated that the climate change mitigation strategies suggested in the Intended Nationally Determined Contribution (INDC) may achieve at least a 22 percent reduction of the overall national GHG emissions by 2030. Besides, among the drivers of biofuels in Uganda is agricultural diversification and rural development. Therefore, apart from informing the ongoing policy developments, this analysis contributes to realizing the above environmental and socio-economic objectives.

Although MEMD aims at a blending level of up to 20 percent, the current vehicle fleet can run on a 10 percent blend without major engine or fuel system modifications. Therefore, this study simulates an ethanol volume adequate for a 10 percent blending in 15 years. Nakamya and Romstad (2020) assess the socio-economic benefits of maize, cassava, molasses, and sugarcane ethanol in Uganda. However, their study is based on a static computable general equilibrium (CGE) model, which may not capture some growth effects. Moreover, they do not consider any environmental constraints such as emissions, which are critical.

This study applies a recursive dynamic Computable General Equilibrium Model (CGE), calibrated to the 2016/17 Uganda social accounting matrix (SAM), with maize, cassava, and sugarcane ethanol. It quantifies GHG emissions from ethanol in Uganda's context while examining the socio-economic impacts of local and foreign capital. The results show the possible socio-economic benefits and shed light on the hotspots along the ethanol supply chain and the necessary safeguards to ensure a sustainable ethanol sector. To my knowledge, this is one of the first empirical analyses in Uganda in line with the national biofuels policies and climate change goals.

The rest of the paper is organized as follows: Section 2 presents the methods and data. Section 3 reports and discusses the results, while 4 provides the conclusion and policy implications.

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[3] This information is found in the Ministry of Energy and Mineral Development sector performance report of 2020.

2.0 Methods and data

2.1 The economy-wide model

The economy-wide model analyzes the macroeconomic effects. It is a recursive dynamic CGE model based on the 2016/17 Uganda official SAM developed by Tran, Roos, Asiimwe, and Kisakye (2019). The model extends the PEP-1-t single-country, recursive dynamic CGE model by Decaluwé, Lemelin, Robichaud, and Maisonnave (2013). The SAM was obtained from the Ministry of Finance, Planning and Economic Development, while data on gasoline imports and prices are from the Ministry of Energy and Mineral Development and the Uganda Bureau of Statistics (UBOS). Ethanol prices were obtained from ethanol processors, and the elasticity parameters and conversion rates are from the literature (see Table A1. Appendix A). This study modifies the SAM version by Nakamya and Romstad (2020), in which they introduce an ethanol sector based on maize, cassava, sugarcane, and molasses[4]. Note that the current model's general structure is also an adaptation of the same work[5].

Production sectors combine the aggregate value-added and aggregate intermediate inputs in a Leontief production function. The same function governs the individual intermediate inputs into the aggregate intermediate input for all the sectors, except for the Ethanol-collecting and Ethanol-blending sectors, which use a constant elasticity of substitution (CES) function. The value-added uses a CES function to combine the labor and the land-capital composites. Labor is categorized into unskilled, semi-skilled, skilled, and highly skilled for both rural and urban. These labor types enter their composite through a CES, and so do capital and land into the land-capital aggregate. The same function combines local and foreign capital.

Domestic output is allocated to the local and export markets under the assumption of imperfect substitutability in a constant elasticity of transformation (CET) function. Total domestic consumption combines domestic production and imports in a CES function. It comprises household consumption, public demand, investment demand, intermediate demand, and the demand for margin services. Uganda is a small country relative to the global market; hence, the analysis assumes exogenous world prices for its imports and exports. However, the model allows exporters to increase their market shares depending on the elasticity of demand and the level of world prices relative to the exports' free-on-board price.

[4] Molasses is dropped in the current study.

[5] This model is an extension of the static CGE by Nakamya and Romstad (2020); hence, a high similarity in the structure.

The current model contains eight households categorized as rural and urban across four income quartiles. These earn income from transfers and factor endowment, and they spend it on consumption and transfers, taxes, and savings. Consumption is modeled as linear expenditure systems derived from the maximization of a Stone-Geary utility function, subject to a budget constraint.

Land and labor are fully employed, grow at constant rates, and are mobile across sectors. The supply of capital is endogenous, and it is determined by the previous period's level of investment and stock of capital adjusted for depreciation. The new capital stock is then allocated across sectors according to their initial share in total capital income and their sectoral profitability rates. Once allocated, it becomes immobile across sectors such that it earns sector-specific rental rates.

Total investment is a function of savings from households, firms, and government plus foreign borrowings. The savings-investment balances are investment-driven, with endogenous savings. Aggregate investment comprises gross fixed capital formation and changes in stocks, whereby the former is a sum of both private and public investment expenditure. The nominal exchange rate is set as the model numeraire, with the real exchange rate adjusting to clear any imbalances on the current account. Government income is a sum of non-tax income from the rest of the world, revenues from taxes on households, and firms' incomes, products, and production activity. Its savings are a flexible residual between revenues and expenditure, which are fixed, and all the tax rates are exogenous.

2.2 The emissions module

The goal of this module is to assess GHG emissions from ethanol relative to the gasoline it displaces. It aims to provide insight into ethanol's environmental sustainability, consistent with Uganda's envisioned emissions reductions by 2030 (MWE, 2015). For this purpose, a cradle-to-grave or well-to-wheels approach is found appropriate (Singh et al., 2010). The system boundary includes feedstock farming, transportation, processing, ethanol transportation and distribution, and fuel combustion. The life cycle inventory stage considers only direct inputs[6]. The functional unit is a liter of fuel, based on which carbon emissions in kg co2eq are determined. Each ethanol type carbon footprint is then calculated and compared. The total net emissions from both gasoline and ethanol are also calculated under various scenarios.

[6] This may not have a signicant impact on the results since most inputs are imported. Besides, the analysis of gasoline emissions only considers combustion and transport.

Details of the calculations are presented in Appendix B. Two general cases are analyzed: one with and another without land-use change with four cases. The conversion factors, emission coefficients, and other parameters are recorded in Table 1.

Table 1 Parameters used in the ethanol LCA analysis

Maize		
Maize yield	2.2t/ha [a]	
Maize ethanol yield	370 l/t [b]	
Fertilizer use	gCO2-eq/kg of fertilizer	kgs of fertilizer/ha
NPK 15-15-15	5,013.33 [c]	100.00 [d]
Urea	3,528.26 [c]	50.00 [d]
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1,552.17 [c]	75.00 [d]
Feedstock transportation	100KM	
Energy in processing	11.12 MJ/L[i]	
Ethanol distribution	200KM	
Converted grassland	26tco2/ha [f]	
Cassava		
Cassava yield	3.2t/ha [a*]	
Cassava ethanol yield	380 l/t [b]	
Feedstock transportation	100KM	
Energy in processing	11.12MJ/L[k]	
Ethanol distribution	200KM	
Converted grassland	26tco2/ha [f]	
Sugarcane		
Sugarcane yield	60t/ha [g]	
Sugarcane cane ethanol yield	80 l/t[h]	
Fertilizer use	gCO2-eq/kg of fertilizer	kgs of fertilizer/ha
NPK 15-15-15	5,013.33 [c]	100.00 [d]
Urea	3,528.26 [c]	160.00 [d]
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1,552.17 [c]	117.00 [d]
Muriate of Potash (MOP) 60%K2O	413.33 [c]	20.00 [d]
Rock phosphate 21%P2O5 23%SO3	95.00 [c]	15.00 [d]
Triple superphosphate (TSP)	543.75 [c]	50.00 [d]
Feedstock transportation	50KM	
Energy in processing	1.69MJ[j]	
Ethanol distribution	200KM	
Converted forest land	26tco2/ha [f]	
	151tco2/ha [f]	
Carbon sequestration	4.1tCO2/ha [e]	
Foregone forest carbon sequestration	5.68t CO2eq/ha/year [f]	

Note: The cassava yield is expressed in terms of dried cassava chips using a conversion factor of 2.4kg/kg.
Parameter source:
[a] MEMD (2016); [b] Vinh, N. T. (2003).
[c] Standard calculation values.v.1.0 https://ec.europa.eu/energy/sites/ener/files/documents/Standard%20values%20v.1.0.xlsx.
[d] Godfrey and Dickens (2015); [e] Thurlow, Branca, Maltsoglou, and Rincón (2016); [f] EPA (2010) report page 391 for forest and 393 for grassland;
[g] FAO (2020); [h] Shumba, Roberntz, and Kuona (2011) and Hartley et al.,(2019); [j] Seabra et al. (2011); [k]Pimentel and Patzek (2005)

Emissions from the farming stage are attributed to the fuel used during plowing for all three feedstocks and planting of only sugarcane. This assumption is justified by the labor-intensive farming practices in Uganda. The emissions from this stage also include those associated with fertilizer application in maize and sugarcane only. It is uncommon to use fertilizers in cassava production in Uganda (Fermont et al., 2010).

The use of fertilizer is still low in Uganda. Therefore, fertilizer emissions are determined according to the fertilizer application rates calculated from the study by Godfrey and Dickens (2015). This study provides a fair picture of fertilizer use in Uganda. The types of fertilizers in this analysis include NPK 15-15-15, Urea, Di-Ammonium-phosphate, Muriate of potash, Rock phosphate, and Triple superphosphate. The feedstocks' input coefficients in the ethanol sub-sectors are used to determine the actual quantities of feedstock into ethanol and the corresponding hectares required to produce it. Fertilizer application rates are then used to calculate the acreage fertilized for each crop. Based on this acreage, the crop yield, and the amount of fertilizer per hectare, fertilizer emissions per liter of ethanol are derived using the relevant emissions factors.

Emissions from feedstock transportation to processing sites are based on a 100km-distance for maize and cassava and 50km for sugarcane. Transportation of all feedstock types assumes a truck with a 20-metric ton carrying capacity and fuel consumption of 0.4 liters per kilometer.

Ethanol processing requires steam and electric energy. Maize and cassava are starch feedstocks; hence, their ethanol processes are assumed to be similar. The steam in both maize and cassava ethanol is assumed to be generated by diesel-fired boilers, and the electricity consumed in the process is hydro-based. The emissions from this electricity are considered insignificant; hence, ignored[7]. Sugarcane ethanol uses bagasse-fired boilers for steam and bagasse electricity. This energy is considered carbon neutral (Carvalho, Segundo, Medeiros, Santos, & Junior, 2019; Kiatkittipong, Wongsuchoto, & Pavasant, 2009; EPA, 2010). The surplus electricity can be exported to the national grid, generating carbon credits to sugarcane ethanol. The emissions discussed above relate to the scenario without new land brought to use.

The scenario with land-use change incorporates emissions from converted grassland and forestland. It involves the carbon released into the atmosphere, foregone carbon sequestration for deforested land, and carbon sequestered by the feedstock crops. This study adopts the definition for carbon sequestration from the EPA (2010) report, describing it as carbon storage in standing vegetation for more than a year. This implies that only sugarcane qualifies in this case, as indicated in Table 1.

[7] Kumar et al., 2011 report a range of 4 -14g co2eq/kwh.

The grassland has a carbon stock value of 26tco2/ha, while deforested land has 151tCO2/ha. Under these two, two different scenarios are considered: all feedstock is grown on converted grassland (scenario 1); only sugarcane is grown on deforested land (scenario 2).

Since ethanol production is increased gradually, land conversion occurs in a phased manner causing a once-off carbon loss from each land clearance. These are calculated based on the acreage, and once emitted, their total does not increase but progressively declines for every extra liter of ethanol produced. This also holds for the carbon sequestered by sugarcane. Foregone carbon sequestration from forestland is added to the sugarcane ethanol emissions at a rate of 1.55t C/ha/year, equivalent to 5.68t CO2eq/ha/year. In contrast to LUC emissions, the per liter emissions from foregone carbon sequestration remain constant for the entire period. Where only one-half of the sugarcane is grown on deforested land, foregone carbon sequestration is also one-half of 1.55t C/ha/year.

Gasoline is the reference fuel displaced by ethanol. Since all the gasoline is imported, its emissions are associated with only transportation and tailpipe. Tailpipe emissions are modeled for ethanol and gasoline as a fixed proportion per liter. Carbon dioxide from ethanol combustion is assumed to be offset by the carbon dioxide captured during feedstock growth; therefore, tailpipe accounts for only methane and nitrous oxide (EPA, 2010; Wang et al., 2012). Both gasoline and ethanol are distributed based on a 200-kilometer distance and a 4000-liter truck with fuel consumption of 0.4 liters per kilometer.

Maize and cassava are non-perennial crops. Therefore, their carbon footprint in farming corresponds to the amount of feedstock and the volume of ethanol produced per period. In contrast, sugarcane is a perennial crop, taking between 18 to 20 months to mature. Therefore, its carbon footprint is annualized to make it consistent with the annual increase of ethanol (see section 2.3 for ethanol simulation).

2.3 Baseline projection and Policy simulations

The baseline projection provides a reference point for the simulations. The population growth rate is set to 3.2 [8] percent. This also determines the growth in skilled labor while unskilled labor grows at 2.2 percent. Total factor productivity also grows at 2.2 percent annually. These trends generate an annual growth rate in real GDP of 5.1 percent. This baseline scenario may not be so realistic, but it attempts to replicate a trajectory of the key demographic and macroeconomic variables based on Uganda's current and historical trends. Furthermore, the major purpose is to evaluate the deviations from the baseline due to ethanol; hence, the findings should still be meaningful.

[8] This is similar to the population growth rate used in a study on Uganda by Twimukye, Matovu, Levine, and Birungi (2011).

Each ethanol type is virtually zero in the base year equilibrium. For a better comparison, each of the three ethanol pathways contributes an equal volume to the total ethanol produced. In the policy simulation, the stock of capital in the ethanol sector is exogenously and gradually increased as producers draw in other inputs until the adequate volume for a 10 percent blending is reached in 2031 (see Hartley et.,2019; Thurlow et al.,2016). This volume is about 0.194 billion liters, based on the projected gasoline consumption of 1.94[9] billion liters by 2031. Gasoline consumption is determined using a growth rate of about 7 percent, calculated from the average annual gasoline import growth rates. Ethanol taxes are set arbitrarily to equate its price to that of gasoline. This assumption means that mandatory consumption and other incentives that attract investment are implicit in the model.

As described in section 2.1, the building blocks in a CGE include consumption, production, and markets. The CLCA approach applied to the energy and environmental module determines the relevant footprints considering the movements in prices, output, elasticities of supply and demand for factors and commodities, and any rebound effects. In the system delimitation, only gasoline is included as the marginal process affected by ethanol production. It is acknowledged that market equilibrium changes may influence production in other activities, but it is not easy to trace their emissions. However, to moderate the impacts of mainly agricultural-based activities, land constraints are released when considering land-use change emissions. Therefore, emissions from all activities other than ethanol and gasoline are held constant, and net emissions from total ethanol and gasoline are determined by comparing the initial and final-year equilibria.

Caveats to the analysis

The recursive dynamic CGE does not solve intertemporal optimization problems, but rather, it is an adaptive model without forward-looking behavior by individuals. However, this may not be a severe limitation as the purpose of the study is to capture the structural linkages and growth effects of ethanol over a relatively short period of 15 years.

Regarding the environmental sustainability module, some emissions are excluded due to data inadequacy—for example, the pesticide emissions. Nonetheless, the use of pesticides in Uganda's agriculture is limited[10]. The analysis also excludes emissions from inputs in processing, such as enzymes

[9] Note that for ethanol volumes up to a10% blend level permit an equivalence of the units of gasoline and ethanol (Macedo et al.(2008).

[10] UBOS (2020). The annual agriculture survey 2018 statistical release. Kampala Uganda. Uganda Bureau of Statistics.

and yeast. These are also expected to have a minor contribution to total emissions [11]. Another limitation is the failure to account for the ratoon sugarcane crop [12], which may misrepresent the amount of fuel and fertilizer used. Nevertheless, it is expected that the findings can still provide a reasonable clue on the nature of emissions and potential hotspots.

3.0 Results and discussion

3.1 Social and Economic impacts

All the results in this section are reported as percentage deviations from the baseline values in the final base year 2031, except otherwise stated. Table 2 reports the macroeconomic and sectoral impacts from employing local and foreign capital.

The new demand for feedstocks by the ethanol industry increases land, labor, capital, and output growth in the feedstock sectors. As a result, the feedstock sectors witness rising prices and revenues. They draw in more land and labor, and the rent and economy-wide wage for each labor type increase. This negatively affects other competing sectors, including the "Cash crops" and "Grain seeds." These are among the main export commodities in the agricultural sector. Moreover, the appreciation of the exchange rate, which occurs because of the significant reduction in gasoline imports, causes a decline in these sectors' exports. These two effects contribute to decreasing output and rising prices of these and other similarly affected activities—accordingly, the economy's average price level rises [13].

Table 2 compares the economic impacts under the two capital scenarios: the foreign and domestic capital cases. Total agricultural output is slightly higher under foreign capital. The effect on the affected sectors is also less severe. This is because only land is reallocated in this case. In contrast, real GDP grows slightly faster under local capital. In the findings, real GDP at basic price grows at 0.04 percent under both scenarios. In comparison, income-based GDP (and nominal GDP at market price) increases by 0.78 percent under foreign capital and 1.02 percent under local capital. Therefore, the differences in real GDP at market price could be attributed to the slightly higher income in the local capital scenario. It is apparent in Table 3 that local capital generates more growth in household income.

The movements in the trade flows and incomes affect the current account. In both scenarios, gasoline imports reduce, leading to local currency appreciation. It appreciates by 0.99 and 0.75 percent under local

[11] Dunn, Mueller, Wang, and Han (2012) find that enzymes and yeast contribute only 1.4% to the farm-to-pump GHG emissions in the production of starch ethanol.
[12] Opposed to plant crop, ratoon sugarcane grows on the stubbles left after harvest. This assumption may inflate the volume of fuel and emissions from this activity.
[13] In Nakamya and Romstad (2020) the prices of contracting sectors decline because they used the GDP deflator as the numeraire.

and foreign capital, respectively. The flow of capital returns to the rest of the world lessens the exchange rate appreciation in the foreign capital case.

Table 2 Macroeconomic and sectoral impacts on local production

		% Deviation from the final base year	
	Baseline growth rate (%)	Foreign capital	Local capital
Real GDP	5.1	0.11	0.13
Total agriculture	5.1	0.14	0.13
Cash crops	5.4	-1.04	-1.14
Grain seeds	5.1	-0.40	-0.39
Maize	5.3	1.80	1.78
Cassava	5.0	1.48	1.51
Sugarcane	5.7	12.57	12.49
Sugar manufacture	5.5	-1.23	-1.27
Forestry	5.6	-0.04	-0.03
Fishing	5.3	0.00	0.01
Mining	5.4	0.00	0.00
Other alcohol	5.3	-0.13	-0.14
Food processing	5.4	-0.15	-0.15
Gasoline	7.0*	-18.06*	-18.04*
Other manufacture	5.8	-0.15	-0.18
Trade	5.2	0.17	0.22
Consumer price index (CPI)	1	0.71	0.87
Real exchange rate	1	-0.81	-0.99

***This is a change in imported volume, not local production.**

In Table 3, expanding ethanol production increases household income in both cases but faster under local capital. Despite the increase in income under both cases, household welfare measured by equivalent variation improves mainly for the richer households. This is more pronounced under the local capital case following the pattern of change in income (see Table 4). The decline in welfare implies an increase in prices exceeding income growth. Furthermore, for the households with lower income levels, expenditure on food is over 50 percent of their total household expenses. Therefore, as food prices increase, their purchasing power deteriorates.

Arndt, Pauw, and Thurlow (2012) and Hartley et al. (2019) assume foreign capital in the feedstocks and ethanol sectors. Their analyses are based on large volumes of ethanol: 1000 million liters for the former and 1400 million liters for the latter. Although the current study simulates a smaller volume of approximately 190 million liters (0.19 billion liters) per year by 2031, movements in the variables such as income, the exchange rate, real GDP depict a reasonably similar pattern.

Government income increases for the whole period under local and foreign capital. Nakamya and Romstad (2020) also find a positive change in government revenues in their static CGE analysis, which is mainly attributed to the high taxes on ethanol. In the present study, the tax is lowered to equate the ethanol and gasoline prices. Nonetheless, government income still rises.

The benefits from foreign capital are lower because of profit repatriation. Furthermore, the nature and small size of the ethanol sector limit the magnitude of its effects. The ethanol volume simulated (0.19 billion liters by 2031) generates benefits in the feedstock sectors. However, as also observed in other studies, the negative impacts from resource reallocation and the exchange rate appreciation tend to produce substantial adverse effects on other economic activities. Export prices rise faster than the import prices, and all exports decline as imports increase, except for gasoline. Therefore, as the net benefits are usually disparate across sectors, it is crucial to pursue strategies that generate more positive benefits to counterbalance the negative impacts, for example, by controlling income outflow.

Table 3 Percentage deviation in household income from the final year baseline value

	Foreign capital	Local capital
RuralQ1	0.78	1.00
RuralQ2	0.79	1.02
RuralQ3	0.77	1.01
RuralQ4	0.77	1.03
UrbanQ1	0.69	0.92
UrbanQ2	0.72	0.97
UrbanQ3	0.77	1.01
UrbanQ4	0.85	1.10

Households are categorized as rural and urban under four income quartiles denoted as Qs.

Table 4 Percentage deviation in household welfare from the final year baseline value

	Foreign capital	Local capital
RuralQ1	-0.06	0.05
RuralQ2	0.03	0.16
RuralQ3	0.09	0.24
RuralQ4	0.29	0.49
UrbanQ1	-0.23	-0.10
UrbanQ2	-0.11	0.05
UrbanQ3	0.12	0.28
UrbanQ4	0.52	0.70

Welfare is measured using Equivalent Variation.

3.2 Results from the emissions module

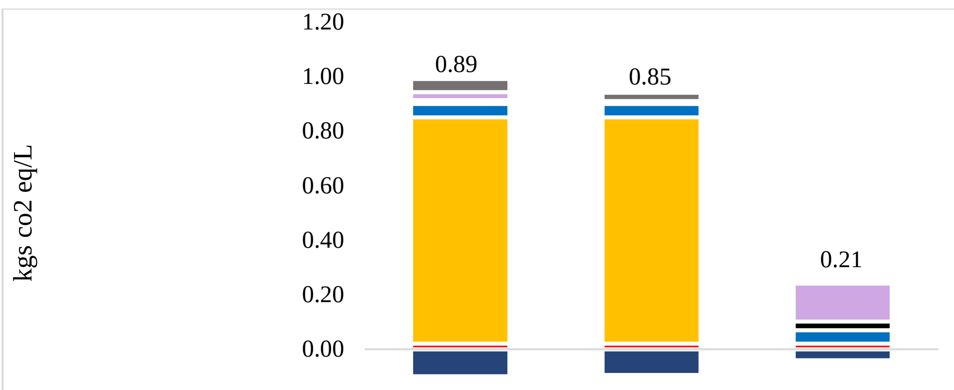
3.2 Carbon footprint results

3.2.1 Per liter GHG excluding land-use emissions

These are presented in Figure 1 and Table 5. Gasoline, the reference fuel, emits 2.33 kgCO2eq/L during combustion and 0.05 kgCO2eq/L in distribution, and the latter is uniform across all the fuels. Life cycle GHG emissions are quantified per liter of each ethanol type. For the maize and cassava ethanol, the processing stage is a significant source of GHGs stemming from the high energy consumption and the assumed diesel-fired boilers. This stage contributes about 84 and 97 percent of the total emissions for maize and cassava ethanol, respectively. These emissions are insignificant and assumed to be zero for sugarcane ethanol because it uses bagasse-based energy, which is considered carbon neutral (Kiatkittipong, Wongsuchoto, & Pavasant, 2009).

The current analysis is characterized by local factors and farming practices in Uganda. As elaborated in section 2.2, sugarcane farming generates higher fertilizer emissions than maize due to the relatively higher fertilizer application rate. However, mechanization causes more emissions in maize and cassava because of the lower productivity per hectare. Emissions from feedstock transportation are also relatively high for all ethanol types but more significant for sugarcane. Despite the shortest distance (50 km) considered, the sugarcane ethanol yield of 80 l/t of cane is relatively low compared to maize and cassava ethanol (see Table 1). Therefore, it takes more metric tons of sugarcane to produce a given volume of ethanol.

Transport and distribution emissions are based on a distance of 200 kilometers for all fuels; hence, these are uniform. Tailpipe emissions are also standard for all ethanol pathways. As already mentioned in the methods section, these are attributed to methane and nitrous oxide; combustion carbon dioxide is assumed to be offset by biogenic carbon dioxide. As shown in Figure 1, co-products account for about 11 percent of the total emissions in maize and cassava ethanol, while surplus electricity accounts for approximately 19 percent in sugarcane ethanol. The proportions are, however, derived from the allocation method applied.



	Maize	Cassava	Sugarcane
Co-product credit	-0.10	-0.09	-0.04
Farm mechanization	0.05	0.03	0.01
Feedstock farming/fertilizer	0.03		0.14
Feedstock transportation	0.01	0.01	0.03
Transport and distribution	0.05	0.05	0.05
Process	0.83	0.83	
Tailpipe	0.02	0.02	0.02
Total emissions without LUC	0.89	0.85	0.21

Figure 1: The carbon footprint of maize, cassava, and sugarcane ethanol without land-use change

Table 5: Emissions in Kg CO2eq/L without land-use change

	Maize	Cassava	Sugarcane	Gasoline
Tailpipe	0.02	0.02	0.02	2.33
Process	0.83	0.83		
Transport and distribution	0.05	0.05	0.05	0.05
Feedstock transportation	0.01	0.01	0.03	
Feedstock farming/fertilizer	0.03		0.14	
Farm mechanization	0.05	0.03	0.01	
Total emissions without co-products	**0.99**	**0.94**	**0.25**	**2.38**
Percentage reduction relative to gasoline	*-58.40%*	*-57.56%*	*85.29%*	
Total emissions with co-products credits	**0.89**	**0.85**	**0.21**	
Percentage reduction relative to gasoline	*-62.61%*	*-64.29%*	*-91.18%*	

3.2.2 Per liter GHG including land-use emissions from grassland

In Table 6, all feedstock is produced on converted grassland with 26t CO2eq/ha, and a 4.1t CO2eq/ha/year carbon sequestration rate is assumed for sugarcane; the latter is maintained for all the LUC cases. Grassland conversion releases more carbon into the atmosphere, raising the immediate total emissions to 29.21, 19.63, and 4.01 kgCO2eq /L for maize, cassava, and sugarcane ethanol, respectively. As observed in the final year values, total emissions per liter decline steadily as production increases.

Given the gradual increase in ethanol production, all ethanol types break even in the reference period (15 years). This occurs when the cumulative emissions from ethanol equal gasoline emissions, as depicted in Figure 2. Cassava and maize ethanol reaches the breakeven point in 13 and 15years, respectively, while this happens in 5 years for sugarcane ethanol. Nevertheless, the breakeven values are still higher than those without LUC emissions. Therefore, all ethanol emissions continue to fall, implying a payback[14] period beyond 15 years.

Table 6: scenario 1- All feedstock cultivated on grassland with a carbon stock value of 26t co2eq/ha

	Maize	Cassava	Sugarcane	Gasoline
Without LUC emissions but with co-product credits	**0.89**	**0.85**	**0.21**	**2.38**
Immediate year LUC emissions	31.46	20.87	5.37	
Carbon sequestration			-0.85	
Carbon credit from co-product	-3.14	-2.09	-0.72	
Immediate year total	29.21	19.63	4.01	
Final year value	**2.34**	**1.81**	**0.39**	
Percentage reduction relative to gasoline	*-27.73%*	*-40.76%*	*-87.82%*	

Note: All emissions are expressed in Kg CO2eq/L.

[14] Payback period is the time it takes to fully offset LUC emissions and reach the carbon-neutral level.

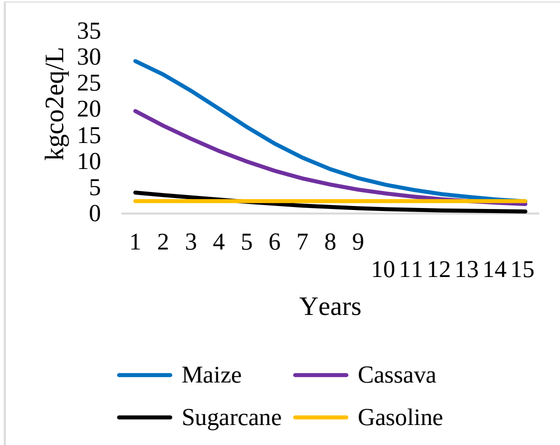


Figure 2: Emissions per liter of ethanol and gasoline (All feedstock on 26 t co2eq/ha grassland)

3.2.3 Per liter GHG including land-use emissions from forestland

The conversion of forest land is only assumed in sugarcane growing. When sugarcane is grown on deforested land, the immediate emissions per liter are the highest for this ethanol type in all the scenarios (see Tables 7). Although it reaches the breakeven point in the reference period, this happens later in 15 years if all production is on deforested land (see Figure 3). Overall, sugarcane ethanol outperforms the other two ethanol pathways. The emissions savings from sugarcane ethanol are primarily attributed to the zero process emissions, carbon sequestration, and the credit attributed to the surplus electricity. Nonetheless, the indication of rising emissions from deforested land is a warning sign of the high risks of encroaching on such land despite the emissions saving potential from sugarcane ethanol.

Table 7: scenario 2- All sugarcane cultivated on forestland with carbon stock value of 151t co2eq/ha

All sugarcane on 151 tco2eq/ha forestland	Sugarcane	Gasoline
Without LUC emissions but with co-product credits	**0.21**	**2.38**
Immediate year LUC emissions	31.18	
Carbon sequestration	-0.85	
Foregone carbon sequestration	1.17	
Carbon credit from co-product	-5.04	
Immediate year total	26.67	
Final year value	**2.37**	
Percentage reduction relative to gasoline	*-0.42%*	

Note: All emissions are expressed in Kg CO2eq/L.

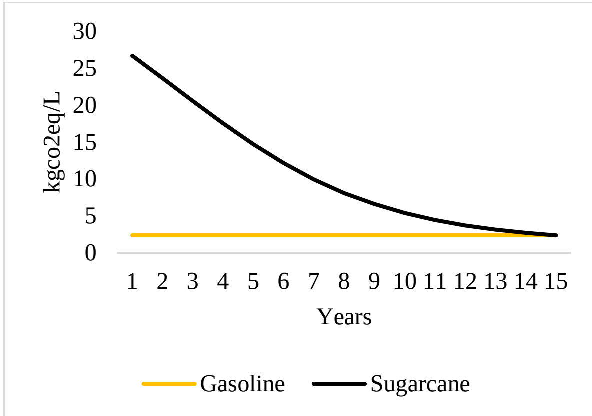


Figure 3: Emissions per liter of sugarcane ethanol and gasoline (All sugarcane on 151 t co2eq/ha forestland)

3.2.4 Overall emissions from ethanol and gasoline

The long-run trend for gasoline demand remains positive but increasing at a decreasing rate because gasoline is being displaced. The same holds for the total emissions; however, these decline faster because the per-liter emissions from ethanol are also declining. From scenario 1, total emissions (from ethanol and gasoline), which are initially higher, fall below gasoline emissions (Figure 4 panel A). Panel B corresponds to scenario 2. It is observed that ethanol may reduce national GHG emissions if feedstock production is limited to grassland. Put differently; new lands brought to use with carbon stock values at least below 26 t co2eq/ha may not reverse the intended emissions reduction.

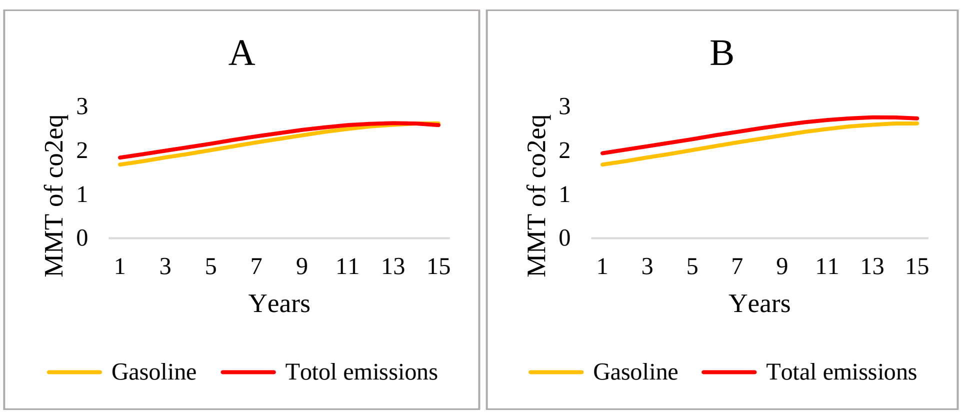


Figure 4: Plot of total and gasoline emissions million metric tons (MMT) of carbon dioxide equivalent.

3.3 Sensitivity analysis

A sensitivity analysis was carried out on the elasticity parameters. Particularly, changes in the elasticity parameters between land, capital, and labor cause marginal changes in the macroeconomic results. However, releasing the land constraint generates more growth and household welfare benefits, but with a pattern similar to the constrained land supply case. That is, local capital still generates higher benefits. The negative impacts on the cash crop sector and other exporting sectors are also minimal.

Regarding the emissions module, variations in the fertilizer parameters cause substantial changes compared to processing energy parameters and the feedstock yield (see Tables 8, 9, and 10). This is mainly observed in maize ethanol. Given the low maize yield, total fertilizer application to all the maize crop implies more hectares, more fertilizer, and more metric tons of GHGs. It is, however, found that the process energy parameter (for maize and cassava ethanol) is more sensitive than the crop yield parameters. This is consequential given the significance of processes energy and the assumption of diesel-fired boilers.

Table 8: 50% increase in yields of all feedstocks

	Maize	Cassava	Sugarcane
With LUC/ 26 kg co2eq/ha	**1.61**	**1.33**	**0.27**
	-32.35%	***-44.12%***	***-88.66%***
50%	1.36	1.17	0.21
Percentage change relative to gasoline	*(-(42.86%)*	*(-50.84%)*	*(-91.18%)*

Source: own computations.

Table 9: 100% fertilizer application in the maize and sugarcane

	Maize	Sugarcane
Baseline (Fertilizer rates (3%, 77%)		
With LUC/ 26 kg co2eq/ha	**1.61**	**0.27**
	-32.35%	***-88.66%***
Fertilizer rates (100%,100%)		
New total emissions per liter	**2.24**	**0.31**
Percentage change relative to gasoline	*(-5.88%)*	*(-86.97%)*

Table 10: 50% increase and 50% reduction in process emissions for maize and cassava ethanol

		MJ/L	Maize Kgsco2eq/l	Cassava Kgsco2eq/l
With LUC/ 26 kg co2eq/ha		11.12	1.61	1.33
			-32.35%	-44.12%
	+50%	16.68	1.98	1.7
Percentage change relative to gasoline			(-16.81%)	(-28.57%)
	-50%	5.56	1.23	0.95
Percentage change relative to gasoline			(-48.32%)	(-60.08%)

Source: own computations.

Comparison with previous studies

Thurlow et al. (2016) examine emissions from sugarcane ethanol in Tanzania, assuming forestland with a carbon stock value of 75.7 t CO_2/ha, grassland with 12.9 t CO_2/ha, and sugarcane carbon sequestration rates of 4.1 and 1.6 t CO_2eq/ha under small and large-scale farming, respectively. This generates about 25 kg CO2eq/L in the immediate year for deforested land, with a carbon payback period[15] of 15 years for large-scale and 27 years for small-scale sugarcane farmers. On the other hand, grassland conversion emits moderate GHGs, reaching a carbon-neutral level relative to gasoline in 2 years for large-scale and 3 years for small-scale farmers. Their processing+transport emissions are higher at 1.25 kgco2eq/L.

Scheunemann et al. (2017) assess GHG emissions from converting grassland to sugarcane for ethanol in Malawi. They adopt the same carbon stock value for grassland as in Thurlow et al. but a sugarcane carbon sequestration rate of 1.22 C/ha (4.47t CO2/ha). Their process emissions parameter is 1.15 kgco2/L. In ten years, a liter of ethanol emits 1.82 kgCO2 for the irrigated outgrower and 1.52 kgCO2 for the rain-fed outgrower schemes. However, when land expansion is restricted, these values drop to 1.37 kgCO2 for the former and 0.91 kgCO2/L for the latter.

The differences between the above two and the current study are the high process emissions and low carbon stock values of converted land. While the present study considers zero process emissions for sugarcane ethanol, its carbon stock values for grassland and forest land are high. Table 11 summarizes additional findings from other studies. Although most of these studies consider emissions from indirect inputs, the high crop and ethanol yield significantly impact the net GHG emissions. Despite the variations in the final values, the analyses portray hotspots and the possible range of emissions consistent with the current study. Notably, processing, fertilizer application, and feedstock farming (land-use change) are significant sources of GHGs.

Table 11: Comparison of findings with earlier studies

	GHG (kg co2 eq/L)			Yield (mt/ha for crops, L/mt for ethanol)					
				Crop	Eth	Crop	Eth	Crop	Eth
	Maize	Cassava	Sugarcane		Maize		Cassava		Sugarcane
The current study	0.99	0.94	0.25						
Mekonnen., 2018	44.9g/MJ		38.5g/MJ	≈11[c]	425			≈75[c]	86
	0.95kg/L		0.81kg/L						
Wang et al	62g/MJ		45g/ML		425				81
	1.31kg/L		0.95kg/L						
Macedo et al., 2008			0.44kg/L						86
Seabra et al., 2011			0.45kg/L[b]						81
Le et al., 2013		0.74kg/L				33	385		

b is calculated from 21.3g/MJ; c approximate values from FAO for US corn and Brazil sugarcane between 2014-2017

4.0 Conclusion and policy implications

This research applies a recursive dynamic CGE model to examine the socio-economic and environmental sustainability of ethanol in Uganda. It examines the implications of local and foreign capital for the socio-

[15]They defined the breakeven point as the payback. Furthermore, they consider a default value of 2.85kgco2eq/L for gasoline GHG life cycle emissions.

economic outcomes and the extent to which ethanol reduces GHG emissions relative to gasoline. Local capital generates more growth effects than foreign capital, with household incomes and real GDP rising faster under the former. However, although income grows in both cases, household welfare measured by equivalent variation improves less for the poorer households. This is because these spend more on food, and as food prices increase, their purchasing power deteriorates.

Without any land-use change, all ethanol types significantly reduce GHG emissions. However, producing feedstock on grassland or forestland releases more carbon into the atmosphere. In the case of converted grassland, it would take 15 years for maize ethanol, 13 for cassava ethanol, and 5 for sugarcane ethanol to break even with gasoline. For sugarcane produced on deforested land, breakeven occurs within 15 years. Nevertheless, all the ethanol has a payback period beyond 15 years. Overall, sugarcane ethanol could contribute to climate change mitigation because of its emissions saving ascribed to the zero process emissions, carbon sequestration, and the carbon-free surplus electricity from bagasse. Maize and cassava ethanol are outcompeted by sugarcane ethanol mainly because of their low crop yields. Therefore, it is essential to improve crop yields and consider other energy sources with lower emissions. The increased yields will benefit ethanol producers and the poor landless as food prices fall and labor demand rises.

The ethanol industry is small in relation to the whole economy, but it substantially impacts other sectors and the current account. From the findings, prioritizing local investors would avoid profit repatriation and attenuate some adverse effects.

This research could be extended to include energy, possible environmental impacts on water consumption and pollution, and biodiversity loss. An integrated model with a poverty module would also provide more insight into ethanol's distributional effects.

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Appendix A

Table A.1 Elasticity parameters

									Consumption parameters	
	CES	CES	CES	CET	CES	CET	CES	CES	Frisch	-1.5
Activity	**Land-Capital**	**Labor types**	**Capital-Labor aggregate**	**Output substitution**	**Armington sub**	**Export sub**	**Ethanol**	**Gasoline-Ethanol**	**Commodity**	**Parameter**
Grain Seeds	0.3	0.6	1.2	2	5	0.72			Grain Seeds	0.7
Maize	0.3	0.6	1.2	2	5	0.72			Maize	0.7
Cassava	0.3	0.6	1.2	2	5	0.72			Cassava	0.7
Sugarcane	0.3	0.6	1.2	2	2	2			Sugarcane	0.7
Other-agric.	0.3	0.6	1.2	2	2	0.7			Other-agric.	0.7
Animal Farm	0.6	0.6	1.2	2	2	1.2			Animal Farm	0.7
Mining	0.6	0.6	1.2	2	2	2			Mining	1.05
Raw Oil	0.6	0.6	1.2	2	2	2			Raw Oil	1.05
Processed food	0.6	0.6	1.2	2	0.6	0.4			Processed food	1.05
sugar	0.6	0.6	1.2	2	0.6	0.4			sugar	1.05
Molasses	0.6	0.6	1.2	2	2	2			Molasses	1.05
Spirit+alchohol	0.6	0.6	1.2	2	2	2			Spirit+alchohol	1.05
Petroleum	0.6	0.6	1.2	2	0.3	2			Petroleum	1.05
gasoline	0.6	0.6	1.2	2	0.3	2			gasoline	1.05
Maize ethanol	0.6	0.6	1.2	2	2	2			Maize ethanol	1.05
Cassava ethanol	0.6	0.6	1.2	2	2	2			Cassava ethanol	1.05
Molasses ethanol	0.6	0.6	1.2	2	2	2			Molasses ethanol	1.05
Ethanol	0.6	0.6	1.2	2	2	2	8		Ethanol	1.05
Blend	0.6	0.6	1.2	2	2	2		120	Blend	1.05
manufacture	0.6	0.6	1.2	2	0.9	0.6			manufacture	1.1
Elec, gas, water	0.6	0.6	1.2	2	0.6	0.6			Elec, gas, water	1.1
Trade	0.6	0.6	1.2	2	0.6	0.6			Trade	1.1
Transport	0.6	0.6	1.2	2	2	2			Transport	1.1
Other services	0.6	0.6	1.2	2	2	2			Other services	1.1
chemicals	0.6	0.6	1.2	2	2	0.6			chemicals	1.1

SOURCE: Adopted from Nakamya and Romstad (2020)

Appendix B

1. Fertilizer emissions

In Table B.1 below, GHGs are summed up for all fertilizer types, and these are expressed in terms kgsCO2eq/ha. Total production and the area used in 2016/17 determine the yield per ha. The yield and the technical coefficients guide in determining the actual value of the feedstock inputs in the SAM, which is applied in calculating actual quantities of inputs into ethanol production. Fertilizers and the corresponding emissions are calculated based on the feedstocks' actual amounts and the yield per ha, determining the land used. Note that not all hectares of land used are fertilized; The fertilizer application rates in maize and sugarcane are used to determine the area fertilized.

Table B.1 Parametric assumptions in feedstock production

Maize	gCO2/kg	gCH4/kg	gN2O/kg	gCO2-eq/kg	kg of fertilizer/ha	grams of co2 e/ha	kgs/ha	Rate
NPK 15-15-15	4,261.33	10.03	1.68	5,013.33	100.00	501,333.33		
Urea	3,296.09	9.29	-	3,528.26	50.00	176,413.04		
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1,459.04	3.73	-	1,552.17	75.00	116,413.04		
Total					**225.00**	**794,159.42**	**794.16**	
Fertilizer application rate								0.03
Sugarcane							-	
NPK 15-15-15	4,261.33	10.03	1.68	5,013.33	100.00	501,333.33		
Urea	3,296.09	9.29	-	3,528.26	160.00	564,521.74		
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1,459.04	3.73	-	1,552.17	117.00	181,604.35		
Muriate of Potash (MOP) 60%K2O	409.20	0.17	-	413.33	20.00	8,266.67		
Rock phosphate 21%P2O5 23%SO3	95.00	-	-	95.00	15.00	1,425.00		
Triple superphosphate (TSP)	516.56	0.87	0.02	543.75	50.00	27,187.50		
Total					**462.00**	**1,284,338.59**	**1,284.34**	
Fertilizer application rate								0.77

2. Emissions from feedstock transportation

Emissions from feedstock transportation are clearly explained in the methods section. The emission factor of 2.5 kgs co2/L is an average of diesel and gasoline emission factors because either fuel could be used in the trucks.

Table B.2 Parametric assumptions in feedstock transportation

Feedstock transportation	Distance	Capacity of truck	Fuel consumption	Emission factor (kgs co2/L)	Emissions/L (**different values for each fuel)**
Maize ethanol and Cassava ethanol					
	100 km	20 t	0.4L/km	2.50	
Sugarcane ethanol	50km	20t	0.4L/km	2.50	
Fuel transportation and distribution					
ALL Fuels	200 km	4000L	0.4L/km	2.50	**0.05**

3. Process emissions

Parametric assumptions maize and cassava ethanol processing

To process a liter of maize or cassava ethanol takes (steam + other energy), that is, Steam 2,646 Kcal/l +9kcal/l for dehydration to pure ethanol, plus 0.392Kwh/l of electricity.

1kcal = 0.004184 MJ,
2,646 Kcal/l +9kcal/l= 2,655 Kcal/l*0.004184 MJ= 11.11MJ/L This case assumes the use of thermal electricity from diesel generators.
One liter of diesel emits about 2.67kgco2, and this contains 35.9 megajoules (MJ).
$\frac{2.67kgco2}{35.9MJ}x11.11MJ = 0.83kgco2.$
0.392Kwh/l of electricity is assumed to be hydroelectricity with insignificant emissions.

Emissions allocation to co-products
Use of maize bran
Maize bran =ush500 at yield of 0.67kg/l
1t = 370l
Bran = 370*0.67=247.9kg *500 = 123,950.
Ethanol = 3000*370 = 1,110,000
Total economic value = 123,950+1,110,000=1,233,950
Share of ethanol = 1,110,000/1,233,950=0.90; bran = 123,950/1,233,950= 0.10

The same share is applied to cassava ethanol.

Table B.3 Parametric assumptions in sugarcane ethanol processing

Processing	**Sugarcane ethanol**					
Sugarcane	Bagasse yield of a metric ton of sugarcane	Steam per ton of bagasse	Electricity in a ton of steam		Process /t	Surplus electricity
1t	0.3t[a]	2t 0.3*2=0.6t	5t steam = 1Mwh 1t steam =1/5 Mwh 0.6t steam =1/5*0.6=0.12Mwh	0.12 Mwh =120Kwh	37.51kwh [16]	82.49kwh

[a] Bagasse is 40% of a metric ton of sugarcane. However, 10% is assumed to be lost in handling, hence, the use of 30%.

<u>Allocation based on market value approach</u>

Price per kwh in Uganda is $ 0.125 = 0.17*3200= USH.554, Ethanol = 3000
In a tonne, ethanol value is 3000*80L/t=240,000
electricity 120 kwh
37.51kwh consumed in ethanol production
82.49kwh is the surplus sold. 82.49kwh*Ush554=45,669
Total economic value of both products = 240,000 + 45,669= 285,669.
Percentage share of ethanol = 240,000/285,669=0.84
Percentage share of electricity = 45,669/285,669=0.16.

<u>Allocation in terms of energy content</u>

82.49kwh*3.6MJ= 296.964MJ
Ethanol 80L*21.1MJ=1,688MJ
Total 1,688MJ+296.964MJ=1,984.964MJ
Ethanol share = 0.85
Electricity share = 0.15

In conclusion, both methods provide almost the same share.

[16] Adopted from Macedo, I. C., Seabra, J. E., & Silva, J. E. (2008). Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and bioenergy*, *32*(7), 582-595.

Table B.4 Parametric assumptions for mechanization and sugarcane carbon sequestration

Mechanization

Mechanization

Coefficient	Actual qty kg/L of ethanol	Yield t/ha	Ha used	Fuel/ha	Emission coefficient	Emissions/L
Maize	2.69kg	2.2	2.69kg/2.2t = 2.69kg/2200kg	15L of diesel	2.67 kgs co2/L	= 2.69kg/2200kg *15*2.67 =0.05
Cassava	2.63kg	3.2	2.63kg/3.2t = 2.63kg/3200kg	15L of diesel	2.67 kgs co2/L	= 2.63kg/3200kg *15*2.67 =0.03
Sugarcane			(12.6kgs/60,000kgs) (12.6kgs/60,000kgs)		2.67 kgs co2/L	(12.5kgs/60,000kgs) *15*2.67 =0.008/L of ethanol Annualize 0.008*1/18*12=0.0053 Both plowing and planting 0.0053*2=0.01kg co2 eq/L

Sugarcane carbon sequestration

	Actual qty kg/L of ethanol	Yield t/ha	Ha used	Emission coefficient	Emissions/L
	12.5kg	60	12.5kgs/60t 12.5kgs/60,000kgs	4.1t co2	(12.5kgs/60,000kgs) *4100kgco2eq 0.85kgsco2eq/L

Foregone forest sequestration

	Actual qty kg/L of ethanol	Yield t/ha	Ha used	Emission coefficient	Emissions/L
	12.5kg	60	12.5kgs/60t 12.5kgs/60,000kgs	5.683t co2	(12.5kgs/60,000kgs) *5683kgs 1.171kgsco2eq/L

4. Blending emissions

The energy used in blending is assumed to be hydroelectricity. This is used in the energy balance but its emissions are considered to be insignificant.

5. Combustion /Tailpipe emissions

As explained in the methods section, combustion emissions are only those from Methane and Nitrous oxide. These were in gco2eq/mmBtu. Because they are measured in the same units, they are summed up. A lower heat value (LHV) of 19992 Btu/L is then used to express them in terms of per liter of ethanol.

Table B.5 Combustion parameters for all ethanol

All ethanol	GHGs	g CO2 eq/ mmBtu	Kgs CO2 eq/ mmBtu	LHV	Emission/L
	NO2	611	0.611	19992 Btu/L	(0.88/1,000,000Btu)*(19992 Btu/)
	CH4	269	0.269		
			0.88		**0.02kgsco2**
Gasoline					2.33kgsco2

Note: 1 L of ethanol = 19992Btu
mmBtu = 1,000,000 Btu