Bioenergy for sustainable development in developing countries

Bioenergi for bærekraftig utvikling i utviklingsland

Philosophiae Doctor (PhD) Thesis

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Dedication

In loving memory of Mr. and Mrs. Aaron Ngirebisa

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To God be the glory forever! He flattens every mountain and raises every valley.

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List of papers

Paper I: Nakamya, M., & Romstad, E. (2020). Ethanol for an agriculture-based developing economy: A computable general equilibrium assessment for Uganda. *Energy for Sustainable Development*, *59*, 160-169. https://doi.org/10.1016/j.esd.2020.10.003

Paper II: Assessment of alternative policy instruments to promote biofuels in developing countries (co-authored with Romstad, E), Working Paper.

Paper III: Nakamya, M. (2022). How sustainable are biofuels in a natural resource-dependent economy?. *Energy for Sustainable Development*, *66*, 296-307. https://doi.org/10.1016/j.esd.2021.12.012

Paper IV: Poverty and inequality implications of biofuels production in low-income incomes, Working Paper.

Summary

The main objectives of this thesis are to evaluate the policies to promote bioenergy in developing countries and to assess the related impacts within the realms of sustainable development. The growing interest in bioenergy and the heavy dependency on agriculture in most developing countries may provide room for economic growth. Large natural resource endowments and low labor costs create comparative advantages in the bioenergy sector and opportunities to alleviate poverty. Bioenergy in the form of first-generation liquid biofuels is one option to exploit, as the technologies are already available and mature. This can generate job opportunities for farmers and those outside the agricultural sector. Moreover, displacing imported petroleum products with locally produced biofuels not only lowers greenhouse gas emissions but can also cut trade deficits. It reduces the heavy economic burden caused by a huge import bill of petroleum and other high-cost imports amid meager foreign exchange earnings from the cheap raw agricultural exports.

However, biofuels may lead to unintended negative impacts if not well managed. For example, production expansion alongside a faster-growing population in developing countries may increase the pressure on the available resources, causing high food prices, food insecurity, increased greenhouse gas (GHG) emissions, excessive water use, and biodiversity loss. Therefore, with benefits on the one hand and imminent trade-offs across multiple sustainability spheres, the promotion of biofuels should aim at maximizing the benefits while controlling the risks across the social, economic, and environmental dimensions.

This thesis adds to existing research on the deployment of biofuels for sustainable development by focusing on ethanol production in Uganda. The overall findings contribute to an evidence-based choice of feedstocks and sustainable biofuel production. Equally essential is the adjustment of Uganda's social accounting matrix (SAM) to a version with an ethanol sector, which is a significant step in moving forward the biofuel discourse in Uganda and similar countries.

I address the overall objectives of this thesis in four independent but related research papers. Paper one examines the economic impacts of ethanol production and mandatory consumption. The paper reports positive impacts on household income and real GDP, and the significant reduction in gasoline imports suggest a possible improvement in the trade balance if exports are sustained.

Paper two evaluates the possible policy tools to promote ethanol. Results reveal a combination of a feedstock and ethanol subsidy as the most suitable instrument. However, the presence of sector-specific capital in agriculture impairs the effect of the subsidies, raising taxpayers' costs.

In paper three, I evaluate the land, water, energy, and carbon footprints. I find that even with land-use change, ethanol would still reduce fuel-related and national emissions. However, this only occurs with grassland conversion but not forestland.

Finally, paper four examines the final impacts of ethanol on poverty and income distribution. There is potential for enhanced household income but no significant impact on the distribution. However, the increase in commodity prices surpasses the growth in income, resulting in rising poverty. These negative effects are nevertheless dampened with improved crop yields.

Based on the performance criteria of economic gains, environmental benefits, and net energy gains, I find ethanol viable and potentially pro-poor for developing countries. However, improved crop productivity is urgently needed as low crop yields significantly influence the outcomes in most of the analyses.

Sugarcane emerged as the most suitable feedstock across all criteria. Nevertheless, using both sugarcane and cassava could avoid escalating prices and redistribute growth across regions. From a policy perspective, a combination of an ethanol subsidy with support for feedstock production will likely cause more robust economic growth. Ethanol has great potential to contribute to climate change mitigation, as exhibited by a decline in national GHG emissions. Nonetheless, forestland should be avoided in feedstock production. Additionally, low-carbon energy should be encouraged in the production processes.

Sammendrag

Hovedmålsetningene med denne avhandlingen er å evaluere virkemidler for å fremme bioenergi i utviklingsland, og vurdere de påfølgende virkningene i forhold til bærekraftig utvikling. Økende interesse for bioenergi og den høye avhengigheten av landbruk i de fleste utviklingsland kan gi rom for økt økonomisk utvikling. Betydelige mengder naturressurser og lave lønninger kan gi komparative fordeler i bioenergi, og dermed også bidra til redusert fattigdom. Bioenergi kan realiseres raskt gjennom første generasjons flytende biodrivstoff etter som det er en tilgjengelig og moden teknologi. Dette kan skape sysselsetting for bønder og folk utenfor landbrukssektoren. Videre vil det å erstatte importerte petroleumsprodukter med lokalprodusert biodrivstoff ikke bare redusere drivhusgassutslippet, men også kutte handelsunderskuddet. Det reduserer den tunge økonomiske byrden skapt av høye regninger fra import av petroleumsprodukter og andre dyre importvarer og magre valutainntekter fra billig råvareeksport fra jordbruket.

Imidlertid kan biodrivstoff føre til utilsiktede negative effekter om ressursene ikke forvaltes riktig. For eksempel kan ekspansjon av produksjonen samtidig med rask befolkningsvekst i utviklingsland medføre et stort press på tilgjengelig ressurser og medføre høye matpriser, redusert matvaresikkerhet, økte drivhusgassutslipp, overforbruk av vann og tap av biodiversitet. Samfunnsøkonomisk nytte av produksjonen av biodrivstoff må derfor avveies mot andre aspekter av bærekraft, ved å maksimere nytten samtidig som en kontrollerer for sosiale, økonomiske og miljømessige effekter.

Denne avhandlingen bidrar til den eksisterende forskningen på hvordan biodrivstoff kan bidra til bærekraftig utvikling gjennom å analysere etanol-produksjon i Uganda. Resultatene bidrar til kunnskapsbaserte valg av råstoff for bærekraftig produksjon av biodrivstoff. Like viktig er det at avhandlingen gjennom å inkludere etanolsektoren i Ugandas nasjonalregnskap tar diskursen omkring biodrivstoff i Uganda og lignende land et signifikant skritt framover.

Jeg adresserer hovedformålet med avhandlingen i fire separate, men relaterte artikler. Artikkel en undersøker de samfunnsøkonomiske effektene av etanolproduksjon og obligatorisk forbruk. Resultatene viser positive effekter på husstandsinntekt og brutto nasjonalprodukt (BNP), og den signifikante reduksjonen i bensinimport indikerer en mulig forbedring i handelsbalansen dersom eksporten opprettholdes.

Artikkel to evaluerer mulige virkemidler for å promotere etanol. Resultatene viser at en kombinasjon av råstoff -og etanol-subsidier er det mest passende virkemidlet. Imidlertid vil forekomsten av sektorspesifikk kapital innen jordbruket redusere effekten av subsidien og øke kostnadene for skattebetalerne.

I artikkel tre vurderer jeg fotavtrykket som etanol har på areal, vann, energi og karbon. Jeg finner at selv om etanolproduksjon medfører endringer i bruken av landområder vil det redusere drivstoffrelaterte og nasjonale utslipp. Dette skjer imidlertid kun når gressletter brukes, og ikke skogområder.

Til slutt undersøker artikkel fire effektene av etanolproduksjon på fattigdom og inntektsfordeling. Det er et potensiale for økt husstandsinntekt, men det er ingen signifikant effekt på inntektsfordelingen. Imidlertid til økningen i varepriser overgå økningen i inntekt, og resultere i økt fattigdom. Disse effektene vil dempes noe av økte avlinger.

Basert på bærekraftskrieriene økonomisk gevinst, miljø-nytte og netto energigevinst, finner jeg at etanolproduksjon er et levedyktig alternativ som potensielt vil kunne være til fordel for de fattige i utviklingsland. Lave avlinger har signifikant effekt på resultatene i de fleste av analysene. Derfor haster det å øke avlingsproduktiviteten for å realisere disse gevinstene. Sukkerrør framstår som det best egnede råstoffet langs alle bærekraftdimensjonene. Kombinasjonen av sukkerrør og kassava kan imidlertid redusere veksten i matvarepriser. Det kan føre til omfordeling av nettogevinster mellom regionene. Fra et politikkperspektiv vil en etanolsubsidie i kombinasjon med støtte til råvareproduksjon skape en mer robust økonomisk vekst. Etanol har et stort potensial for å bidra til å bremse klimaendringene gjennom å redusere nasjonale drivhusgassutslipp. Imidlertid bør en unngå å bruke skogområder til råvareproduksjon til biodrivstoff. I tillegg bør det oppmuntres til bruk av lav-karbon energi i produksjonsprosessene.

1. Introduction

The overall objectives of this thesis are to evaluate the policy interventions to promote bioenergy and to assess the socioeconomic and environmental impacts. Bioenergy is renewable energy produced from biomass, an extensive resource in most developing countries. Developing countries, particularly Sub-Saharan Africa, have considerable potential to produce bioenergy due to surplus land and the current unproductive and inefficient agricultural systems (Smeets et al., 2004). The inefficiency provides room to exploit economies of scale in agriculture through improved farming practices. Therefore, with the growing interest in bioenergy and the over-dependency on agriculture, such features and the availability of resources create comparative advantages in bioenergy production. Modern bioenergy in the form of liquid biofuels is one pathway to economic growth and poverty alleviation (Mudombi et a., 2018). Moreover, the technologies for first-generation biofuels like ethanol and biodiesel are already available and mature (Ho, Ngo, & Guo, 2014; Mittal & Decker, 2013).

Biofuels present high prospects for energy security and self-sufficiency in fuel supply when substituted for imported fossil fuels. Africa is an excellent example to illustrate this point. Most of the few countries endowed with oil reserves are primarily net exporters of crude oil and, at the same time, net importers of petroleum products. This has resulted in a high number of petroleum products importing countries on the continent (Amigun et al., 2011). The high dependency on imported petroleum products makes these countries vulnerable and less resilient to surges in world oil prices. Moreover, the expenditure on these products and other high-cost imports imposes a heavy economic burden amid meager foreign exchange earnings from the cheap raw agricultural exports. Therefore, displacing imported fossil fuels with locally produced biofuels may improve the trade balance. Biofuels and the production of feedstocks may also enhance socio-economic wellbeing through employment, agricultural market expansion, and increased household income (Hartley et al.,2019). From an environmental perspective, carbon sequestration during feedstock growth and the displacement of fossil fuels may reduce greenhouse gases (GHGs), contributing to the efforts to mitigate climate change.

However, with high poverty levels and a faster-growing population in developing countries, biofuel expansion may exert tremendous pressure on the available resources, leading to unintended negative impacts. For instance, studies have shown at least a partial influence of biofuels on food prices and food insecurity (Gilbert, 2010; Rosegrant, 2008; Zilberman et al., 2013; Tyner, 2013). There are also concerns regarding land-use change (LUC) emissions (Fargione et al., 2008; Searchinger et al., 2008; Acheampong et al., 2017) and emissions from intensive farming, as well as risks of excessive water use and the loss of biodiversity. With benefits on the one hand and imminent trade-offs across multiple sustainability spheres, biofuel policies should aim at production that maximizes sustainability across the social, economic, and environmental dimensions.

Sustainable development is a broader version of the sustainability concept defined to encompass a sustained increase in societal and individual welfare (Dixon & Fallon,1989). According to the Brundtland Report, sustainable development requires meeting the needs of the current generation without compromising the ability of future generations to meet their own needs (Brundtland, 1987). In the United Nations sustainable development goals (SDGs) context, the role of bioenergy is apparent despite not being explicitly stated. For example, availing locally produced and perhaps affordable clean energy contributes to SDG 7. At the same time, long-term environmental gains are possible when biofuels offset greenhouse gas emissions, reducing the mean global temperature increments and enhancing crop yields (Subramaniam et al.,2020). These outcomes are associated with SDG 13 and 2, respectively, and could also contribute to SDG 3 through improved health conditions. In addition, employment opportunities and the enhancement of household income relate to decent work and economic growth as well as declining poverty (SDGs 8 and 1). Rising incomes also enable the attainment of quality education (SDG 4).

Moreover, SDGs 5, 9, 10, 11, 14, and 15 can also be indirectly influenced. For instance, rural development may reduce the rural-urban economic divide and curtail rural-urban migration (Cororaton& Timilsina, 2012), which lessens the population in slums. Additionally, gender disparity may diminish with improved agricultural income since women predominate agriculture in most developing countries. Nonetheless, while increased household income may yield affordability of farm inputs, which increases food production (SDG 2), Subramaniam et al. (2020) emphasized that biofuels' enhancement of food security would be contingent on improved environmental quality.

Therefore, it all points to sustainable resource use and maximization of benefits while minimizing the negative impacts. However, what rate of resource use should be considered sustainable? In this regard, a common argument is that when uncertain of what sustainable development entails, market forces should be allowed to influence the rate of resource use and induce solutions to scarcity (Dixon and Fallon, 1989). Nevertheless, the limitations of a free-market economy may call for policy and other forms of government intervention to correct likely market failures. Given the factors surrounding biofuels, a similar notion holds worldwide with regard to the success of most biofuel industries. In light of the above discussion, the highlighted trade-offs may have significant implications, particularly for the low-income agriculture-dependent economies. Typically, most of these economies rely on natural resources for their livelihood and have higher population growth rates. This exposes them to risks of declining per capita resources, resource misuse, and climate change. Even so, the impacts of biofuels tend to differ due to variations in production systems and feedstock types (Peskett et al., 2007; Jeswani, Chilvers, & Azapagic, 2020). They are also bound to vary according to livelihood sources, soil carbon contents, and climatic conditions.

Most research on biofuels has been done in developed economies (Calzadilla, Delzeit, & Klepper, 2014; Taheripour, Levano & Tyner, 2017; Elizondo & Boyd, 2017). In this regard, the implications of biofuel in poor natural resource-dependent economies are still a matter of investigation. Notable contributions for developing countries include Arndt et al. (2010), Amigun et al. (2011), Schuenemann et al. (2017), Boccanfuso et al. (2018), Hartley et al. (2018), and Hartley et al. (2019). Despite the similarity of issues in these studies, there has not been a fully integrated assessment of policies, socio-economic impacts, and in-depth evaluation of the relevant environmental footprints, particularly in developing countries.

Therefore, in this thesis, I aim to carry out an integrated assessment of policies to promote ethanol [1] and examine the socio-economic and environmental impacts using the case study of ethanol in Uganda. These broad aims are addressed in four specific research questions corresponding to four independent but related research papers in the chapters that will follow. First, what socio-economic impacts might ethanol production and mandatory blending have on Uganda's economy? Second, what are the possible policy instruments to promote a nascent ethanol industry amid budget constraints and the goals of energy security, rural development, and emission reduction? Third, how sustainable are biofuels in a natural resource-dependent economy? Fourth, what are the likely poverty and inequality implications of biofuel production for the low-income countries?

This thesis is organized into five chapters. The following section of this first chapter, i.e., section two, is an overview, synthesis of papers, and key contributions. Section three summarizes the current state of production and consumption of biofuels. Section four, with its corresponding subsections, presents the data and methods, while section five summarizes the main findings and research contributions. Finally, section six provides policy implications and the conclusion, while section seven concludes with limitations and future research. The subsequent four chapters are a compilation of the four research papers.

[1] I focused on ethanol since our field visits revealed more willingness by investors to process ethanol than biodiesel.

2. Overview of the thesis, synthesis of papers, and key contributions

The demand for feedstocks in ethanol production is expected to expand the market for agricultural output, affecting prices, factor use and employment, and household income. These micro-level changes could influence macro numbers like real wages and the trade balance through adjustments in imports and exports. Such outcomes and the extent to which they occur have socio-economic implications at the sectoral and macro levels, as well as distributional effects on households. Paper one examines these aspects, and paper four assesses the final impacts on poverty and the distribution of income.

Ethanol has a lower energy content than gasoline, and its production competes with other activities for resources. In this regard, it may be undersupplied or cause food scarcity and rising GHGs emissions. This necessitates government policies and incentives, as witnessed elsewhere. Hence, paper two assesses the possible policy tools to promote production and consumption, while paper three evaluates the environmental footprints. Table 1 on the following page provides a snapshot of these papers, summarizing the specific research questions, modeling approaches, and findings.

Table 1. Snapshot of the thesis

Paper	Main research question	Specific research questions	Major Datasets	Empirical methods	Main findings
I	What socio-economic impacts might ethanol production and mandatory blending have on Uganda's economy	1. What are the economic impacts of ethanol on (i) employment, output, and prices, (ii) household income and welfare, and (iii) the trade balance, government income, and overall economic growth? 2. What is the suitability of each feedstock?	2016/17 Uganda Official SAM	Static CGE	• Factor employment and output would increase, with a moderate rise in commodity prices. • Real GDP would grow moderately, and income increase mainly for rural households. • Household welfare would decline due to a counter-financing tax. • If exports are maintained, the significant decline in gasoline imports would result in an improved trade balance. • Sugarcane and maize are more growth-enhancing compared to cassava. • The use of molasses may result in escalating prices, and an average of multiple feedstocks would be more sustainable.
II	What are the possible policy instruments to promote a nascent ethanol industry amid budget constraints and the goals of energy security, rural development, and emission reduction?	1. What is the appropriate policy for Uganda's ethanol industry given the financial constraints? 2. What implications may capital specificity have for the ethanol policy outcomes?	2016/17 Uganda Official SAM	Static CGE	• All policy instruments lower gasoline consumption, but only the subsidies improve welfare. • The ethanol consumption subsidy takes the smallest budget and performs well, but it exerts upward pressure on food prices. • The feedstock subsidy generates substantial gains but requires a large resource budget. • Despite the high government income from the gasoline tax policy, it also raises commodity prices and erodes household welfare. • A two-part instrument of a feedstock and ethanol consumption subsidy is the most suitable. • The presence of sector-specific capital impairs the subsidy effect and raises the financing burden.
III	How sustainable are biofuels in a natural resource-dependent economy?	1. How energy efficient is the ethanol from maize, cassava, and sugarcane? 2. What is the water footprint of each ethanol pathway? 3. To what extent can ethanol reduce GHG emissions relative to gasoline, and what is the impact on overall emissions? 4. How much land is required in proportion to the total available agricultural land?	2016/17 Uganda Official SAM	Dynamic recursive CGE	• All three pathways have positive energy balances and lower carbon footprints in the absence of land-use change. • It would take between 6 to 15 years for ethanol to break even with reference to gasoline in terms of emissions if land-use change is involved. • The ethanol processing stage and feedstock farming are key emission hotspots. • There is emissions-reducing potential from ethanol exhibited by the decline in national emissions. • Overall, sugarcane ethanol is superior to maize and cassava ethanol. • Land requirements are minimal, and this demand diminishes with improved crop yields.
IV	What are the likely poverty and inequality implications of biofuel production for the low-income countries?	1. Will increasing crop prices and income growth reduce poverty in Uganda and similar developing countries? 2. What are the likely implications of ethanol production and resource reallocation for the distribution of income? 3. What would be the appropriate recommendations?	2016/17 Uganda Official SAM + 2016/17 Uganda National Household Survey	Dynamic recursive CGE + Microsimulation model	• There is potential for enhanced household income but no significant impact on the distribution. • The increase in commodity prices surpasses the growth in income, resulting in rising poverty. • Enhancing feedstock yields dampens the effect on poverty.

2.1 Key contributions

Aside from being the first attempt to empirically examine the potential impact of ethanol production with an explicit displacement of gasoline in Uganda and similar countries, this thesis makes notable contributions to existing literature. First, the thesis adopted a best-practice stance. It extends the understanding of the implications of biofuels in developing countries by assessing the socio-economic impacts of production and mandatory ethanol consumption. Considering a less ambitious volume for domestic use is a more realistic assumption that fits in the current state given the vehicle restrictions and trade barriers developing countries face, as well as the sustainability standards that may be restrictive. Second, it evaluates policy options while taking into account structural rigidities in developing countries' factor markets. Third, the assessment of the environmental footprints and the carbon payback period is fundamental in selecting pathways that minimize the negative impacts. The results also shed light on the emission hotspots, which can be targeted or scrutinized further. Finally, decomposing the ethanol impacts on poverty by the relevant variables facilitates identifying the contribution of each variable. This is crucial as it offers decision-makers a clue on each variable depending on the individual impact. Most importantly, the methods and findings can be conveniently replicated to advance the meager research on the sustainability of biofuels, especially in Africa.

3. The current state of biofuel production and consumption

Globally, the share of biofuels in road transport energy demand was about 4.8 percent in 2019. Pre-pandemic total production was approximately 162 billion liters in 2019, of which 115 billion liters was ethanol. Biofuel markets are currently dominated by US corn and Brazil sugarcane ethanol with a gradual increase in biodiesel. The US and Brazil constitute over 80 percent of the global ethanol production, while the EU is well known for biodiesel. The trend in other countries like China, Thailand, Indonesia, and Argentina, among others, is also promising (International Energy Agency (IEA), 2020). The biofuel industry in most countries has mainly thrived on policies such as mandatory consumption, carbon-neutral standards, and fiscal incentives. Despite being one of the primary ways to decarbonize the transport sector, current biofuel production is not yet on track to achieving this objective. For instance, the IEA Net Zero Emissions by 2050 scenario requires annual average growth of 14 percent up to 2030, up from the current growth of 5 percent (IEA (2021).

3.1 Biofuels in developing countries and the biofuel industry in Uganda

The production of biofuels in developing countries presents a unique opportunity in the face of the ever-failing agricultural policies, unreliable shallow markets with exploitative middlemen, and limited access to regional and international markets. However, the full biofuel potential is yet to be realized. In this thesis, I focus the discussion on African developing countries, mainly Sub-Saharan Africa. The purpose is to put the findings in context by taking advantage of the significant similarities across these countries regarding socio-economic, climate, and geological conditions.

Zimbabwe and Malawi pioneered the production and blending of ethanol with gasoline in Africa as early as the 1980s (Mitchell, 2011; Deenanath, Iyuke, & Rumbold, 2012). While the blending has been sustained up to date and efforts made to integrate the biofuel industry into the countries' economies, a lot remains wanting in terms of policy and governance to ensure sustainable production and foster sustainable development. This is witnessed in the non-accelerated growth of the industry as the operations have been largely on small and medium scales (See Amigun et al., 2011). The situation is not different in other countries like Nigeria, Ethiopia, Tanzania, Kenya, Zambia, and Mozambique. However, for Mauritius, there have been significant strides in expanding the production and exportation of sugarcane ethanol to the EU (United Nations Conference on Trade and Development (UNCTAD), 2006).

Uganda presents a suitable case study of a low-income and natural resource-dependent economy. The country has a tropical climate with annual average rainfall and temperature of about 1188 mm and 25^0 C, respectively, creating high agriculture potential. Sugarcane optimum yields are about 60 tons per hectare, which is closely compared with the 74 t/ha for Brazil (FAO, 2020). While the acreage productivity of maize and cassava is only about 2 tons and 3 tons per hectare, respectively (UBOS, 2017), this suggests much room for improvement through enhanced yields. The average contribution of agriculture to total GDP is about 24 percent, with over 64 percent of the working population engaged in agriculture (Uganda Bureau of Statistics (UBOS), 2018a). The current national poverty rate is 20.3 percent, 23.4 percent for rural, and 11.7 percent for urban, having changed from 21.4, 25.2, and 9.5 percent, respectively, in 2016/17 (UBOS, 2021). There has been continuous government effort toward value-added agriculture to improve farmers' returns, coupled with strategies to reduce vulnerability to climate change through adaptation and mitigation measures. However, the government has yet to deliver on these policy areas.

Since pre-independence, government efforts have been geared toward enhancing agriculture as a potent force in alleviating poverty. Agricultural support through demonstration farms, advisory services, extension services, and value addition has not been effective, and the lack of reliable markets for agricultural commodities remains a big challenge. It is, therefore, reasonable to expect expanding domestic crop markets driven by the increase in demand for feedstocks.

As one of the climate change strategies, the country is at the initial stages of designing and implementing biofuels and climate change policies. A biofuels act was passed in 2018 to regulate biofuel production, distribution, and consumption. It was followed by a Biofuels General Regulations draft in 2020 to guide the initial blending of 5 percent for ethanol and biodiesel [2]. 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) (MEMD, 2020), but this has not been achieved. Companies like Kakira sugar works limited in Jinja and the Sugar Corporation of Uganda limited in Lugazi already have the capacity to produce more than 100,000 liters of ethanol per day. These companies and other small jaggery mills currently produce Extra Neutral Alcohol (ENA) as they await the government to enforce consumption and provide additional investment incentives. Regarding the climate change policy, a 22 percent reduction of the overall national GHG emissions by 2030 relative to the business-as-usual is anticipated from the suggested climate change adaptation and mitigation strategies in the Intended Nationally Determined Contribution (INDC) (Ministry of Water and Environment (MWE), 2015).

MEMD identified cassava and sugarcane in its Biofuels General Regulations as some of the candidate ethanol feedstocks. Although maize was not included in the regulations document, information obtained from the field visits shows that it is one of the primary raw materials, besides sugarcane, in the current production of Extra Neutral Alcohol. The average contribution of the food crop sub-sector to Uganda's GDP is about 13 percent. Among Uganda's 16 major food crops, maize and cassava come in close second and third positions, respectively, after plantain banana, in terms of production and area planted. Sugarcane is also a significant cash crop (UBOS, 2020a). According to Uganda's Annual Agriculture Survey of 2018, maize is grown by over 55 percent of the agricultural households, while 29 percent grow cassava (UBOS, 2020b). On this account, I selected maize, cassava, sugarcane molasses, and sugarcane for the analyses.

4. Data and Methods

This section only presents an overview of the methods and data used; detailed explanations are found in individual papers. The thesis adopts a broader approach inclined toward Von Maltitz and Stafford's (2011) perspective in evaluating the sustainability of biofuels by considering opportunities weighed

[2] This information is found in the Ministry of Energy and Mineral Development sector performance report of 2020 (MEMD, 2020).

against constraints and risks. Rather than focusing on specific sustainability principles and criteria as applied to specific projects, I emphasize identifying best practices that maximize the benefits while controlling for risks. Therefore, the data and methods briefly presented in the next sections are suitable in this regard.

4.1 Data

Two datasets are employed: the 2016/17 Uganda official Social Account Matrix (SAM) and the 2016/17 Uganda National Household Survey (UNHS). The SAM was obtained from the Ministry of Finance, Planning, and Economic Development, while UNHS data is from the Uganda Bureau of Statistics (UBOS). Additional data on gasoline import volumes and prices were obtained from the Ministry of Energy and Mineral Development (MEMD) and UBOS, respectively, and ethanol prices are from ethanol processors. The elasticity parameters, conversion rates for ethanol, and the parameters used to calculate the environmental footprints were obtained from the literature. While the SAM is used as the main dataset for all four papers, it is augmented by the UNHS data to run the microsimulation model in paper four. The original SAM consisted of 186 activities and commodities, and these were aggregated into 34 activities and commodities after introducing maize, cassava, sugarcane, and molasses ethanol sectors. The UNHS dataset contained 15,672 successfully interviewed households from all the districts of Uganda, with data on personal details and variables such as education level, household consumption expenditure, and household income, among others. The estimated population at the time was 37.7 million people, with an unemployment rate of 9.1 percent and a national poverty rate of 21.4 percent (UBOS (2018b).

Note: Elasticity parameters, conversion coefficients, emission factors, and the detailed model adjustments are found in the supplementary materials at: https://doi.org/10.1016/j.esd.2020.10.003 (papers one and two) and https://doi.org/10.1016/j.esd.2021.12.012 (three and four).

4.2 Methods

The interconnectedness of biofuel production with other sectors of the economy and the ensuing trade-offs require a modeling framework that balances the benefits against the adverse effects. This warrants consideration of all the sectors that biofuel is part of, such as agriculture, energy, and other land-based activities, as well as the characteristics of the biofuel supply chain (Azapagic et al., 2017). Besides, substituting ethanol for imported gasoline and the impact on some economic activities can cause significant indirect effects as well as adjustments in the trade account. Accordingly, I apply both static and dynamic computable general equilibrium (CGE) models in this thesis. I use a static CGE in papers one and two and a recursive dynamic CGE in papers three and four.

I augment the dynamic CGE in paper four with a microsimulation model to evaluate the possible distributional and poverty effects of ethanol. The CGE models are run using GAMS software, while the micromodel is implemented in STATA, using the Distributive Analysis Stata Package (DASP) by Araar and Duclos (2013). These modeling approaches are suitable and commonly used in investigations similar to those in this thesis.

Specifically, CGE models apply a representative household assumption. They are suitable when the scope of analysis encompasses sectoral and market inter-linkages, movements in variables such as the exchange rate, and changes at the sectoral and macro level, as used in paper one. They are also suitable for policy assessment as applied in paper two and when indirect and feedback effects along the whole supply chain are relevant, such as in paper three. On the other hand, the microsimulation model is built from data on individuals and households. This allows estimating poverty and income distribution while considering household and individual heterogeneity effects, as in paper four.

Economic theory explicates the production, distribution, consumption of goods and services, and the role of resource and output markets. Features, such as the number of economic agents, their behavior, and the nature of information in a market, determine the equilibrium price and quantity outcomes. These factors influence the degree of competitiveness in markets with corresponding welfare implications. In this context, the analysis of economic agents' behavior in response to price changes is best represented by market equilibrium models such as the partial equilibrium (PE) and CGE models (Van Tongeren, Van Meijl, & Surry, 2001).

While the optimizing behavior of economic agents and market equilibrium outcomes can be analyzed in a PE framework with minimal data requirements, a ceteris paribus assumption and focus on a specific market neglect the critical inter-sectoral linkages (Van Tongeren et al., 2001; Diao et al., 2012) and feedback effects. And despite the apparent advantage of detailed analyses of the directly affected market, PE models fail to account for resource constraints that may apply to some factors of production and their reallocation across sectors.

On the other hand, general equilibrium modeling takes into account the co-movements in all market variables as well as sectoral and economy-wide linkages (Diao et al., 2012). Although it misses out on the detailed analysis, it captures both the direct and indirect effects of a policy or exogenous shock to an economic system. CGE models are rooted in general equilibrium theory, which draws on the Walrasian theory of general equilibrium. They assume perfectly competitive markets, with both consumers and firms as price takers, each too insignificant to influence the price or quantity, and all markets clear. Replication of production technologies by other firms is possible, and firms cannot experience increasing returns to scale due to the price-taking assumption. Hence, production technologies exhibit constant returns to scale.

With the above assumptions, standard CGE models are built in a neoclassical framework with macroeconomic and microeconomic foundations of economic agents' optimizing behavior. However, because of the limitations of perfect competition with regard to the real functioning of economies, CGE models are frequently adjusted for structural rigidities that may be inherent in economies, such as those in developing countries (Diao & Thurlow, 2012). This is implemented through model closures for the factor markets and the macroeconomic balances. For example, the static CGE in this thesis assumes labor unemployment and immobility of some labor types and capital across some activities. I also make some assumptions regarding the macroeconomic balances, as I explain in the model closure section.

According to Walras theorem, a solution exists in analytical general equilibrium models when the number of equations equals the number of unknowns. Nonetheless, its existence does not guarantee its uniqueness. However, as discussed in Sinko (1992), Arrow & Debreu (1950s) proved the existence of a unique solution of a general equilibrium system when: (1) at a set of non-negative prices, demand equals supply in each market; (2) the excess demand functions are homogeneous of degree zero in prices; and (3) excess demand functions are single-valued, continuous, and bounded from below. Under these conditions and other restrictive assumptions, a unique solution is proved using Brouwer's fixed point theorem, and it is also necessary that it is stable.

Computational techniques started with earlier works by Leif Johansen (1960), Arnold Harberger (1962), and Scarf (1967), as described in Shoven and Whalley (1984). Unlike analytical models, a well-specified computational model (CGE) satisfies the condition of being a square system of equations such that the number of equations is equal to the number of endogenous variables. The model is able to find a unique solution numerically through an iterative process (Sinko, 1992). Besides, a homogeneity check through perturbation of the model numeraire is also recommended to test the model validity.

4.3 The static CGE model

A static CGE is a short-term model whereby some factors of production are fixed in supply and may also be immobile across alternative uses. The SAM data contains three primary factors of production: land, labor, and capital, making up the aggregate value-added input. Land is absent in the original SAM, but I incorporated it as cropland using a share of 75 percent of total capital in crop-producing sectors. This share was adopted from the Uganda SAM by Randriamamonjy and Thurlow (2016), and it is similar to the share in the Mozambique SAM by van Seventer (2015).

The production functions are Leontief functions at the top level, combining aggregate value-added and aggregate intermediate inputs in fixed proportions (Equations 1 & 2). Individual intermediate inputs are also modeled in a Leontief function, except for the blending sector that uses a constant elasticity of substitution (CES) function. This was a convenient way to simulate ethanol. I set the elasticity of substitution at 120 to model ethanol and gasoline as perfect substitutes—for only the volume adequate for the 10 percent blending[3]. The capital [4] and labor composites also enter their aggregate value added through a CES function in Equation 3. Given the profit-maximizing behavior of firms, the optimal demand for each input is reached when its marginal revenue product and price (marginal cost) are equal. At the bottom level of each nest, components of capital and labor composites are also combined in a CES function. Profits are maximized when the marginal revenue product of each unit of labor and capital category is equated to its price (wage rate or rental rate).

$$VA_j = v_j XST_j \quad (1)$$

$$CI_j = io_j XST_j \quad (2)$$

$$VA_j = B_j \left[\beta_j \ LDC_j^{-\rho_j} + (1 - \beta_j) \ \ KDC_j^{-\rho_j} \right]^{-\frac{1}{\rho_j}} \quad (3)$$

Where j is an index for industries, VA_j aggregate value-added, v_j the value-added Leontief coefficient, XST_j total aggregate output from industry j, CI_j aggregate intermediate consumption by industry j, and io_j the intermediate Leontief coefficient. In Equation 3, the Bs are scale parameters, βs share parameters, and ρs elasticity parameters. LDC_j and KDC_j refer to labor and capital demand, respectively.

The household sector model component consists of 32 representative household types grouped according to regions: Central, Eastern, Northern, and Western Uganda. Each regional grouping is further categorized as rural and urban and ranked by income quartiles. A relatively high number of households allows the assessment of the macroeconomic impact on different household types at a more disaggregated level. Households earn income from factor payments and transfers from firms, other households, the government, and the rest of the world. They spend this income on consumption, taxes, savings, and transfers. The household consumption demand functions are linear expenditure systems (LES) expressed in Equation 4. These are derived from the maximization of a Stone-Geary utility function subject to a consumption expenditure constraint.

[3] Ethanol volumes up to a10% blend level permit an equivalence of the units of gasoline and ethanol (Macedo et al.(2008).
[4] Capital composite comprises physical capital and land.

$$PC_i C_{i,h} = PC_i C_{i,h}^{min} + \gamma_{i,h}\left[CTH_h - \sum_{ij} PC_{ij} C_{ij,h}^{min}\right] \quad (4)$$

i is an index for commodities and h for households, PC_i is the purchaser price of the commodity, $C_{i,h}$ the consumption of commodity i by household h, and $C_{i,h}^{min}$ the minimum consumption of commodity i. CTH_h is the household consumption budget while $\gamma_{i,h}$ is the marginal expenditure share of commodity i for household h, and the term in parathesis corresponds to the available supernumerary income after allocating minimum consumption expenditure.

The adopted CGE model allows multi-products by a single activity, and total output is aggregated using a constant elasticity of transformation (CET) function in Equation 5. Likewise, domestic output is directed to the domestic and export markets, governed by a CET. In contrast, domestic absorption captures domestic and imported commodities in a CES function for Armington aggregation. Finally, the model adopts a small country hypothesis whereby export and import prices are exogenously determined.

$$XST_j = A_j\left[\sum_i \delta_{j,i} XS_{j,i}{}^{\rho_j}\right]^{\frac{1}{\rho_j}} \quad (5)$$

A_j is a scale parameter, $\delta_{j,i}$ the share parameter, ρ_j the elasticity parameter, and $XS_{j,i}$ the output of product i from industry j.

4.3.1 Model closures

The choice of model closures is largely dependent on the economy's structure. While the supply of land and skilled labor should have been fixed in the static CGE (Van Tongeren et al., 2001), it was appropriate to assume underutilized land and unemployment of labor as these characterize most developing countries. These closures have commonly been used in Uganda's CGE models to represent the underutilization of land and labor in the economy (see Shinyekwa and Mawejje, 2013). Additionally, unskilled labor is only mobile in agriculture; it cannot relocate to other activities because of skill limitations. Land is also assumed to be mobile across crop sectors [5]. Capital is sector-specific in agriculture but mobile in non-agricultural sectors. The mobility in some sectors was invoked to introduce the new ethanol sectors while holding total capital stock constant.

The macroeconomic balances include the savings-investment account, government balances, and external balances. The saving-investment balances are savings-driven with fixed household saving rates and endogenous investments. Note that total savings are allowed to vary. However, foreign savings (the current account balance) are fixed, and the real exchange rate adjusts to clear any imbalances on the

[5] Land mobility in this case implies flexible usage across alternative activities.

current accounts. This closure suites Uganda's case since it runs close to a flexible exchange rate policy. The GDP deflator, Consumer price index, and nominal exchange rate were all used as model numeraires in different papers, and relevant explanation is provided accordingly.

4.4 The dynamic CGE

The static CGE model was transformed into a recursive dynamic CGE by updating certain exogenous variables to introduce dynamic equations [6]. This allows to capture the transitional path and to track ethanol impacts over the entire period. In particular, population growth is introduced. Labor, land, total factor productivity, the autonomous element of household consumption, recurrent government expenditure, and capital accumulation are updated exogenously to form the baseline scenario as elaborated in papers 3 and 4. Land and labor are mobile across activities, growing at constant rates. The supply of total capital is endogenous, and it is determined by the previous period's level of investment and stock of capital adjusted for depreciation. These adjustments generated a baseline annual growth rate in real GDP of 4 percent.

4.5 Modeling ethanol in a computable general equilibrium model

Although biofuels production started as early as the 1970s in Brazil and the US, the development of the biofuels sector is recent, hence, absent in most social accounting matrices (SAMs) for most economies. Therefore, studies have taken different approaches (Kretschmer & Peterson, 2010). Some studies have modeled biofuels implicitly by simply determining the required amount of biomass to produce a given volume (See Dixon et al., 2007; Banse et al., 2008). In others, the biofuel industry is introduced as a latent sector assumed to be unprofitable and therefore inactive in the baseline equilibrium but becomes profitable with government support or changes in relative prices (Kretschmer, Peterson, & Ignaciuk, 2010). Yet, in some, the sector is explicitly disaggregated from existing SAMs, and this is only possible when production already exists but is captured under other sectors (Taheripour et al., 2007).

Currently, there is no fuel-grade ethanol production in Uganda, except for the Extra Neutral Alcohol (ENA) and industrial spirits. Therefore, I model ethanol as a latent sector by introducing a tiny amount in the 2016/2017 SAM. In other words, ethanol output is practically zero in all the base-year scenarios.

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[6] The dynamic equations can be found in the supplementary material to paper two found online at https://doi. org/10.1016/j.esd.2021.12.012. Other key model equations are presented in the supplementary materials of the individual papers while the full models can be obtained from https://www.pep-net.org/pep-standard-cge-models#1-1;

Output is forthcoming only when the sector becomes competitive through the policy scenarios. These include subsidies, taxes, mandatory consumption, and an exogenous increase in capital demand for the ethanol sectors.

4.6 The microsimulation model

The microsimulation (MS) model is built from the UNHS dataset. As earlier discussed, the MS model is built from data on individuals and households, allowing estimation of poverty and distributional effects while taking into account household and individual heterogeneity. In contrast, the CGE model is the representative household assumption, and it only estimates changes in sectoral and macro variables. Based on these differences in modeling capacities, the two models are frequently combined to analyze sectoral, macro, and "between household groups" effects (CGE), as well distributional and poverty effects (MS).

There are various approaches to linking CGEs to MS models. One is a fully integrated approach in which representative households in the CGE are replaced by the actual households from the household survey data (see Cockburn, 2006; Cororaton & Cockburn, 2005; Boccanfuso & Savard, 2007, 2008; Cockburn, Corong & Cororaton, 2010). This approach, however, poses the disadvantage of a lack of some behavioral relations, such as regards to occupational choice, and it also requires data reconciliation (Estrades, 2013). The second category is the top-down sequential models, which are run separately. A variant of these is the top-down accounting approach. With this approach, changes in commodity prices and income from the CGE are passed on to the MS to calculate changes in real income and generate poverty estimates. Despite its simplicity, it does not consider behavioral responses by economic agents, which are incorporated in a parallel approach—the top-down microsimulation with behavioral responses (Chen & Ravallion 2003; Tiberti, Cicowiez & Cockburn, 2017).

While the top-down MS with behavioral responses also lacks feedback effects to the CGE as the top-down/bottom-up approach (Savard, 2005), it is simple. Moreover, its features in terms of a behavioral model comprising the income-generating and household consumption modules are quite appealing. Hence, I adopted this approach as elaborated in paper four.

5. Summary of main findings and scientific contribution

This thesis contributes to the promotion and development of the biofuel industry in developing countries by simultaneously evaluating the policies and the impacts within the context of sustainable development. This section highlights the main findings with reference to the main research questions that form the four research papers. It summarizes the specific research questions, novelty, methodological approach, and key results. More elaborate presentations and discussions are found in the papers.

Paper I

For an agriculture-based economy, the prospective benefits of biofuels cannot be overemphasized, especially in a developing country like Uganda, where over 60 percent of the population depends on agriculture for a livelihood. These benefits range from employment and rural income enhancement to trade and economic growth (Mitchell, 2010). As biofuels production expands, factor demand in this sector and other related industries is expected to rise. And as owners of the factors of production, households may experience a rise in incomes (Mudombi et al., 2021; Nkolo, Motel, & Djimeli, 2018); Al-Riffai & Laborde, 2010).

Moreover, given the heavy dependence on imported petroleum products, substituting some of these products with biofuels can reduce the countries' trade deficit. For example, Uganda imports all its petroleum products, and these constitute the largest share (18.2 percent) of the total import budget (Uganda Bureau of Statistics (UBOS), 2018). However, despite the foreign exchange saving, there are concerns about the imminent loss in import tax revenues. The research question relating to the first paper is addressed by explicitly examining: the economic impacts of ethanol on (i) employment, output, and prices, (ii) household income and welfare, (iii) the trade balance, government income, and overall economic growth. We also evaluate the suitability of the feedstocks. Our empirical analysis is carried out using a static CGE model calibrated to the 2016/17 Uganda's social accounting matrix (SAM), to which we introduced maize, cassava, sugarcane, and molasses ethanol. The simulations assume a 10 percent blending mandate, achieved through a consumption subsidy. This choice is made since at least all modern cars can run on such a fuel mixture without any engine or fuel system modifications. We also find this target less ambitious for an infant industry.

The novelty of our study is the introduction of an ethanol sector in Uganda's SAM and the explicit simulation of a 10 percent blending mandate. To our knowledge, this is the first study in Uganda to empirically examine the likely impact of ethanol production with an explicit displacement of gasoline. Our study highlights the possible impacts of ethanol by presenting general predictive considerations. Specifically, we find that factor employment and output would increase, with commodity prices rising sluggishly. Real GDP would grow moderately, and income increase mainly for the rural households. Household welfare would decline because of the counter-financing tax on gasoline, and it would also be curtailed by land constraints. Reducing gasoline imports would improve the trade balance if exports are sustained, and despite the ensuing decline in import tax revenues, government income would remain positive. Our results suggest that ethanol production is a potential pro-poor project for developing countries like Uganda. Both sugarcane and maize are more growth-enhancing compared to cassava. However, the use of molasses from the sugar industry alone may result in negative impacts, as evidenced by the significant increase in prices. We also observe that using an average of multiple feedstocks would be more sustainable and diminish the rise in prices.

Paper II

Biofuels have noticeable advantages, but it is also true that these fuels are less competitive relative to fossil fuels in terms of production costs (Hill et al.,2006) and energy content. Additionally, production may lead to unintended socio-economic and environmental risks if not well managed. Besides, consumer acceptance also matters in terms of fuel preferences (Moula, Nyári & Bartel, 2017). In this regard, government policies and support become indispensable in ensuring reliable supplies and steady biofuel markets. In economies with flourishing biofuel industries, such as the US, Brazil, and the EU, active policies lie at the heart of this development. Similarly, the promotion of biofuels in low-income countries may not be achieved without government intervention.

Low-income countries face the challenge of limited financial resources on the one hand and policies that fail to deliver on the other. Biofuel development will, therefore, largely depend on how well suited the actual policies are to the conditions in the economy. The rationale for many policies is to correct market failures (Rajagopal & Zilberman, 2008). In relation to an infant ethanol industry, the under-provision of an emission-reducing fuel (ethanol) and the uncertainty that impedes new investments constitute a market failure. Likewise, traffic congestion and air pollution from gasoline are other negative externalities that may warrant government intervention.

Therefore, this paper evaluates the possible policy instruments to promote a nascent ethanol industry amid budget constraints and the goals of energy security, rural development, and emissions reduction by answering the following questions. What is the appropriate policy for Uganda's ethanol industry given the financial constraints? What implications may capital specificity have for the ethanol policy outcomes? These questions are addressed using a static CGE model. We evaluate the feedstock subsidy, an ethanol consumption subsidy, a combination of the two subsidies, and a consumption tax on gasoline as alternative policies. The evaluation is based on the size of the subsidy budget and the impacts on agricultural output, prices, total value-added, real GDP, government income, the trade balance, household income, and welfare. Finally, we consider the environmental effect implicitly through changes in fuel consumption.

Our contribution is the extension of the current literature on biofuels to developing countries in an evaluation of multiple policy options. Second, considering capital specificity allows us to account for the intersectoral differences between agricultural and other capital. This is relevant since we are analyzing the ethanol industry in the short run. To our knowledge, this is one of the few empirical macroeconomic assessments of ethanol policies in low-income countries and the first in Uganda. The study shows that the ethanol consumption subsidy takes the smallest budget and performs reasonably well but leads to rising food prices. On the other hand, the feedstock subsidy generates substantial gains across all indicators but requires a large resource budget. Despite the high government income from the gasoline tax policy, commodity prices rise and erode household welfare. The presence of sector-specific capital in agriculture impairs the effect of the subsidies, raising the financing burden. Finally, a two-part instrument of a feedstock and ethanol consumption subsidy is the most suitable.

Paper III

Research has revealed how the production and consumption of biofuels involve complex and adverse effects. The benefits may be realized at the expense of high food prices, increased GHGs emissions, excessive water use, and other negative impacts. On the one hand is research that underscores the socio-economic benefits of biofuels (see Huang et al., 2012; Portale, 2012; Campbell, Anderson, & Luckert, 2016; Zilberman et al., 2013; Gebreegziabher et al., 2018; Hartley et al., 2019), and on the other, are Life Cycle Analyses (LCA) focusing on environmental aspects such as energy and carbon footprints. Rational and effective biofuel policies should consider all the pillars of sustainability (Nazari, Mazutti, Basso, Colla & Brandli, 2020). It is, therefore, necessary to investigate biofuel impacts while taking into account economic adjustments and the entire supply chain. However, only a handful of studies have simultaneously investigated the socio-economic and environmental impacts. Besides, the impacts of biofuels across different settings cannot be generalized given the disparities in production systems, livelihood sources, feedstock types, soil carbon contents, and overall geographical conditions. Furthermore, an evaluation of attainable production targets for domestic use could be helpful, particularly at the initial stages of the biofuel industry. Moreover, no carbon or other footprints have been estimated for the suggested feedstocks in Uganda's biofuel programs and many other developing countries.

In this paper, I conduct a comparative evaluation of maize, cassava, and sugarcane ethanol, emphasizing land requirements and the environmental sustainability of the three ethanol pathways. This is achieved by answering the following research questions. How energy efficient is the ethanol from maize, cassava, and sugarcane? What is the water footprint for each ethanol pathway? To what extent can ethanol reduce GHG emissions relative to gasoline, and what is the impact on national emissions? How much land is required in proportion to the total available agricultural land?

A two-step approach to Consequential Life Cycle Assessment (CLCA) in a recursive dynamic CGE is applied, and a volume adequate for a 10 percent blending within 15 years is simulated. The results shed light on the hotspots along the ethanol supply chain, which can be targeted for improvement to ensure a sustainable ethanol industry. Furthermore, the research contributes to the meager literature on the sustainability of biofuels, especially in Africa and developing countries. All three pathways have positive energy balances with lower carbon footprints in the absence of land-use change. It would, however, take between 6 to 15 years for ethanol to break even with reference to gasoline if feedstocks were produced on converted grassland.

The ethanol processing stage and feedstock farming are key emission hotspots, but a decline in national emissions indicates ethanol's emissions-reducing potential. Sugarcane ethanol is superior to maize and cassava ethanol, and its benefits derive from the carbon-neutral co-product electricity and a relatively higher ethanol yield per hectare. Land requirements are minimal, and this demand diminishes with improved crop yields. Overall, there are high prospects of economic and environmental gains. However, agricultural investment and immediate attention to the poor crop yields are required alongside a regulated framework and the promotion of low-carbon energy sources.

Paper IV

Agriculture is a predominant source of livelihood for the largest population in most developing countries. This places biofuel programs at the forefront of these countries' development agendas. Biofuel's potential to reduce poverty is premised on the demand and market expansion for crops and the growth in factor employment. The price relationship between biofuels and crops is precisely presented and empirically examined in various papers considering biofuels conversion yields (De Gorter & Just, 2008; Drabik, 2011; Lapan &Moschini, 2012; De Gorter, Drabik, & Just (2013). These papers invariably confirm a positive price relation, which may further be reshaped by biofuel policies in place (Drabik, Ciaian& Pokrivčák, 2016). Rising crop/food prices and increased activity in farming can enhance agricultural income. Whether the increasing food prices and growth in income translate into lower poverty levels is an empirical question.

Some researchers contend that higher food prices are not necessarily detrimental but can lead to declining poverty levels (Van Campenhout, Pauw, & Minot, 2018). Similar findings have also been suggested regarding biofuel production (Arndt, Benfica, Tarp, Thurlow & Uaiene,2010); Arndt, Pauw, & Thurlow, 2010; Boccanfuso, Coulibaly, Savard &Timilsina, 2018). It is, however, essential to note that factors such as feedstock types may have a considerable influence on the outcome. The final impact will also, in part, depend on how quickly agricultural supply and wages respond to price changes (Headay, 2014, 2018). Furthermore, the share of the feedstock crops in the consumption basket, as well as individual and household characteristics, will also determine the magnitude of the price effect. Additionally, where food production and traditional exports may decline, it raises another question whether the economic benefits of biofuels will surpass these risks, particularly in countries with considerable numbers of poor food consumers.

The following questions are therefore pertinent. Will increasing crop prices and income growth reduce poverty in Uganda and similar developing countries? What are the likely implications of ethanol production and resource reallocation for the distribution of income? What would be the appropriate recommendations given the outcomes regarding the above question?

The study uses a recursive dynamic CGE and a microsimulation model to examine the potential impact of ethanol production on poverty and income distribution. The findings show high potential for enhanced household income. However, the concomitant increase in commodity prices surpasses the growth in household incomes, resulting in rising poverty. While the increase in poverty is modest, it reflects an imminent danger from increasing food prices. Enhancing feedstock yields dampens commodity prices and lowers poverty. Hence, despite the comparative advantages in agriculture, developing countries may fail to realize the full benefits of biofuels at the current agricultural productivity levels. Therefore, biofuel policies should be jointly pursued with improved agricultural productivity and efficiency in order to expand and sustain the biofuel industry. Lastly, it is mostly the rural unskilled labor wage that rises most, but the overall findings show no significant changes in the distribution of income.

6. Policy implications and conclusion

As developing countries embrace biofuels for their multiple benefits, sound policies and governance are still lacking, yet these are essential to ensure production that fosters sustainable development. The critical element is evidence-based policies that consider all the dimensions of sustainable development. This thesis uses a fully integrated approach to evaluate biofuel sustainability in four individual research papers.

Based on the findings summarized in section 5, I make the following conclusions and policy recommendations.

First, the criteria of socio-economic competitiveness, environmental benefits, and net energy gains reveal that ethanol production would be viable and potentially pro-poor for developing countries. Sugarcane emerged as the most suitable feedstock along all sustainability dimensions; however, the combined use of sugarcane and cassava might avoid escalating prices and redistribute growth across regions. The envisaged benefits of using molasses from the sugar industry may be overstated. Molasses is currently used in other economic activities, and its use for ethanol causes a significant increase in prices.

Second, from the policy assessment, a combination of an ethanol subsidy with support for feedstock production will likely cause more robust growth than a single policy tool.

Third, biofuel production has great potential to reduce emissions, as exhibited by the decline in national GHGs. Nonetheless, feedstock production on forest land should be avoided. Additionally, low-carbon energy should be encouraged to counteract energy-related emissions.

Fourth, model results suggest that the short-run growth effects are conditional on surplus land, an assumption that might not hold with a continuous expansion of biofuel production. Also, note that despite the higher economic gains associated with both sugarcane and maize ethanol in Paper one, the benefits from maize are reversed in Paper three. This is because of the higher GHG emissions attributed to a lower crop yield. Moreover, crop yields had a significant impact in all the assessments. They significantly influenced commodity prices, poverty levels, environmental footprints, and the demand for land. Therefore, agricultural investment and immediate attention to poor crop yields are required alongside a regulated framework and promotion of low-carbon energy sources.

In conclusion, improving research, government support, and ongoing infrastructural development may eventually expand farm output. Biofuel is one avenue for value-addition and a potential solution to constrained market access in the face of trade barriers and hard-to-meet quality requirements that developing countries face.

7. Limitations and future research

Some limitations were encountered mainly due to methodological and data constraints. First, modeling national emissions using an emission intensity does not account for the dynamics in carbon efficiency. Second, the linear allocation of LUC emissions only shows the breakeven point relative to gasoline. Therefore, it would be interesting to extend this research to applying a discount factor and an ethanol production time horizon to account for variations in GHG emissions. Third, only direct LUC emissions are considered; hence, expanding the system boundary to indirect and other excluded direct inputs would provide additional insight. Fourth, the employed crop model estimates only approximate water use, which does not account for variations in weather conditions. Therefore, this research can be extended to a model that captures uncertainty in crop yields.

Regarding the data, the adoption of elasticity parameters primarily from the literature may not accurately match the model parameters for Uganda and the represented countries. Additionally, land is not explicitly recorded in Uganda's SAM. Introduced cropland fails to account for any land substitution across activities other than crop farming. Investigations can be extended to rich data on land with agricultural ecological zones.

Overall, my analysis in the context of sustainable development has not been exhaustive. Specifically, several social and environmental issues were not considered. For example, issues of land rights, working rights and conditions, health and safety, gender, water pollution, and a deeper analysis of food availability and nutrition are lacking. Further investigations on these issues would be worthwhile.

Despite these limitations, this thesis richly contributes to the literature on biofuels. It extends the discourse to developing countries, providing relevant insights that are essential in the policy formulation and implementation phase. Besides, the methods applied can be conveniently replicated in other research.

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Paper I

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Ethanol for an agriculture-based developing economy: A computable general equilibrium assessment for Uganda

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ABSTRACT

This study uses a static computable general equilibrium (CGE) model to examine the potential economic impacts of ethanol production in Uganda. We introduce an ethanol sector in the 2016/17 Uganda's social accounting matrix (SAM) using maize, cassava, sugarcane, and molasses as feedstocks. Furthermore, we evaluate the suitability of each feedstock. By simulating a 10% blending mandate, we find that factor employment and total output would increase, with a sluggish rise in commodity prices. Real GDP would grow moderately, and household income increase, mostly for the rural households. Household welfare would decline because of a counter-financing tax on gasoline. A reduction in gasoline imports is likely to improve the trade balance, and despite the ensuing decline in import tax revenues, government income would still rise. Our results are suggestive of ethanol production as a potential pro-poor project for Uganda. Both sugarcane and maize are more growth-enhancing compared to cassava. The use of only molasses from the sugar industry may result in negative impacts since it is already an input in other activities. We also observe that using an average of multiple feedstocks would be more sustainable. Moreover, it would allow a more balanced growth while reducing upward price pressures.

Introduction and motivation

Ethanol is one of the conventional liquid biofuels mainly used in transport and industrial processes. Biofuels production started as early as the 1970s in Brazil and the US, and later in the EU (Runge & Senauer, 2007). It has been motivated by concerns for energy security, rural development rural, and the reduction of greenhouse gas emissions. The attempt to promote renewable energy in Uganda was first spelled out in the provisions of the Energy Policy (Ministry of Energy and Mineral Development (MEMD), 2002) and the Renewable Energy Policy (REP) (MEMD, 2007). One of the policy objectives in the latter is to promote the production and utilization of biofuels by setting a requirement of at least a 20% blend level. The biofuels Act was signed in 2018 to provide a supportive regulatory framework that would regulate the production, distribution, and use of biofuels. The Act, however, is yet to be operationalized.

The promotion of biofuels in Uganda is anticipated to reduce the country's trade deficit. Uganda imports all its petroleum products, and these constitute the largest share (18.2%) of the total import budget (Uganda Bureau of Statistics (UBOS), 2018). While substituting some of these products may result in significant foreign exchange savings, there are concerns about the subsequent losses in import tax revenues.

For an agriculture-based economy, a bioeconomy[1] provides a competitive advantage and opportunities to achieve several sustainable development goals (goals 1, 2, 7, 8, 9, and 13). The prospective benefits of biofuels cannot be overemphasized, especially for a country like Uganda, where over 70% of the population derive their livelihood from agriculture. These benefits range from employment and rural income enhancement to trade and economic growth (Mitchell, 2010). As biofuels production expands, factor demand in this sector and other related industries is expected to rise. This can boost the income of households by supplying factors of production. Al-Riffai and Laborde (2010) find that ethanol and biodiesel would improve the income of households in Peru. The increase in household income could potentially dampen poverty levels and even improve food security. For example, Arndt, Benfica, Tarp, Thurlow, and Uaiene (2010), Arndt, Pauw, and Thurlow (2010), and Boccanfuso, Coulibaly, Savard, and Timilsina (2018) assess the expansion of biofuels production using computable general equilibrium (CGE) models, which are linked to microsimulation modules. Their findings suggest a decline in the poverty rates, especially

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[1] Activities involving the use of bio-based resources to produce food, energy and materials.

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for the rural households. In this regard, biofuels production could be perceived as a strategic route to escape from poverty (Peskett, Slater, Stevens, & Dufey, 2007).

Since the pre-independence period, the Ugandan government has made efforts toward enhancing agriculture through extension services and value addition. Nonetheless, the lack of a reliable market for agricultural commodities remains a big challenge. Majority of studies have confirmed a positive correlation between biofuels and feedstock (and food) prices (see Elizondo & Boyd, 2017; Timilsina, Beghin, Van der Mensbrugghe, & Mevel, 2010; Wianwiwat & Asafu-Adjaye, 2013). It is, therefore, logical to expect that promoting biofuels would strengthen crop markets, especially in periods of excess harvest, during which prices usually plummet. The rise in feedstock/food prices may, however, lead to food insecurity, particularly in lean seasons (Mitchel, 2008). Nonetheless, the magnitude of this price increase is quite debatable, as reflected by the variations in findings across studies. Some studies have found a weak relationship between biofuels and food prices; for example, in the work by Wianwiwat and Asafu-Adjaye, the prices of food and other products increase marginally both in the short and long run.

The choice of an appropriate feedstock is also crucial, and it heavily depends on the available technologies. The current technology in Uganda supports production of ethanol from molasses and crops. Policymakers should, however, act with prudence to ensure that the supply of feedstocks does not compromise food availability, and the choice of feedstock crops may have a significant bearing on this. Some crops employ more labor and other factor inputs, others have higher crop yields, yet others have stronger linkages with other sectors in the economy. Arndt et al. (2010) observe that even without any yield improvements, cassava is more profitable, and it generates higher levels of pro-poor growth than sugarcane. Similarly, Hartley, van Seventer, Samboko, and Arndt (2018) find that in Zambia, cassava would generate substantial gains relative to sugarcane and sweet sorghum because it has the highest value-added.[2] Nonetheless, sugarcane is identified to have stronger linkages with the rest of the sectors in the economy.

There is a large body of literature on biofuels at the global level, and this is mainly focused on production in developed countries (see Calzadilla, Delzeit, & Klepper, 2014; Taheripour, Levano & Tyner, 2017; Timilsina et al., 2010; Tyner, Taheripour, Zhuang, Birur, & Baldos, 2010). These studies provide useful insights and an essential basis for research in developing countries. There is also a growing strand of research on this subject in developing countries, but this is still in its early stage (see Arndt, Benfica, et al., 2010; Arndt, Pauw, & Thurlow, 2010; Boccanfuso et al., 2018; Hartley et al., 2018; Hartley, van Seventer, Tostão, & Arndt, 2019). Moreover, biofuels are a new development; they are still understudied, particularly in developing countries.

Our main research question is: what impacts might ethanol production and mandatory blending have on Uganda's economy? We address this question by explicitly examining the economic impacts on (i) employment, output, and prices, (ii) household income and welfare, (iii) the trade balance, government income, and overall economic growth. We also evaluate the suitability of the feedstocks. We carry out our empirical analysis using a static CGE model calibrated to the 2016/17 Uganda's social accounting matrix (SAM). All the simulations assume a 10% blending mandate, which is achieved through a consumption subsidy. Despite the ministerial document (the REP) that aims for at least a 20% blending level, we find a 10% level to be more realistic. Currently, at least all modern cars can run on such a fuel mixture without any engine or fuel system modifications. Besides, this is a less ambitious target for an infant industry. The novelty of our study is the introduction of an ethanol sector in Uganda's SAM and the explicit simulation of a 10% blending mandate. To our knowledge, this is the first study in Uganda to empirically examine the likely impact of ethanol production with an explicit displacement of gasoline. This is a time when knowledge and information are needed for investors and policymakers to make informed decisions. Our study, therefore, sheds light on the possible impacts of ethanol by presenting general predictive considerations. It also provides policy recommendations and a basis for further research.

The rest of the paper is organized as follows: Section 2 briefly introduces biofuels and the background of Uganda's biofuels sector. Section 3 outlines the methods and data, while Section 4 presents and discusses results. In Section 5, we conclude and provide policy implications.

Biofuels and the state of the biofuels sector in Uganda

Biofuels are biomass-based fuels derived from plant or animal material. These may be solid, liquid, or gaseous. The most common liquid biofuels are ethanol and biodiesel, which are mostly used in transport and industries. Ethanol and biodiesel can be blended with gasoline and diesel, respectively. Biofuels from food crops are referred to as first-generation biofuels. While first-generation biodiesel is obtained from oilseed crops, first-generation ethanol is produced from feedstocks that contain sugar; for example, sugar beet, sugarcane, and molasses. It can also be obtained from starch crops such as maize, cassava, banana, and sweet sorghum.

Uganda's biofuels sector is at its initial stage, but companies like Kakira Sugar Works Limited (KSWL) in Jinja and the Sugar Corporation of Uganda Limited (SCOUL) in Lugazi already have installed capacity to produce 35,000 l and 60,000 l of molasses ethanol per day, respectively. SCOUL produces maize ethanol as well. These companies currently process undenatured ethanol known as Extra Neutral Alcohol (ENA), and they have expressed interest to start producing fuel-grade ethanol. A clear regulatory framework and incentives toward the sector are still lacking (MEMD, 2015). This partly explains the slow investment and the delay to commence commercial production. Some small-scale companies like Kamtech logistics in Lira, which was processing 4000 l of cassava ethanol per day, shut down due to lack of a steady market.

The tropical climate in Uganda, with an annual average rainfall of about 1188 mm and temperature of around 25 °C, presents prospects for higher agricultural output. According to the FAO (2020) database, as of 2018, Uganda's sugarcane optimum yield was about 60 t/ha, which compares closely with the 74 t/ha for Brazil. The acreage productivity of maize and cassava were estimated at 2.6 t/ha and 5.3 t/ha, respectively. Although these figures are slightly below the Africa's averages of 2.04 t/ha for maize and 9.08 t/ha for cassava, and the world averages of 5.9 t/ha for maize and 11.3 t/ha for cassava, there is room for productivity improvement. These conditions create a conducive environment for first-generation ethanol. As a preliminary step, the National Environment Management Authority (NEMA) report identifies *Jatropha curcas*, maize, sugarcane, and oil palm as potential biofuels feedstocks (NEMA, 2010).

Materials and methods

Our analysis employs the 2016/17 Uganda's official SAM developed by (Tran, Roos, Asiimwe, & Kisakye, 2019). The SAM and the data on gasoline imports were obtained from MEMD. Data on molasses production, its price, and the price of ethanol is from the sugar industry. We got the ethanol conversion rates from the sugar industry and the literature, and the information on how molasses is captured in the national accounts was obtained from UBOS.

The biofuels sector is linked to other sectors like energy, transport, and agriculture, and these have linkages with other industries. CGE is a suitable modeling framework to account for such interlinkages. We, therefore, carry out our analysis in a static CGE model, and calibrate it to the 2016/17 SAM using GAMS.

Kretschmer and Peterson (2010) present a comprehensive discussion of the approaches to modeling biofuels in CGE analyses. These include implicit modeling, the latent approach, and explicit disaggregation. An implicit modeling approach determines the required

[2] Value-added in this case refers to the contribution of land, capital and labor per unit of output.

amount of biomass to produce a given volume of biofuels (see Banse, van Meijl, Tabeau, & Woltjer, 2008; Dixon, Osborne, & Rimmer, 2007). In contrast, the latent approach introduces a biofuels sector and treats it as unprofitable and inactive in the base year, but it becomes profitable with changes in relative prices or some government support (see Boeters, Veenendaal, van Leeuwen, & Rojas-Romagoza, 2008; Kretschmer, Peterson, & Ignaciuk, 2010). The above two approaches apply when no production exists. If production exists, and it is captured under some other industries, the sector can be modeled by explicitly disaggregating it from the existing database (see Taheripour, Birur, Hertel, & Tyner, 2007).

At the global level, CGE models based on different versions of the Global Trade Analysis Policy database are used in analyzing biofuels (see Calzadilla et al., 2014; Taheripour et al., 2007; Taheripour et al., 2017; Tyner et al., 2010). At the national level, individually built country-specific and generic models, such as the Standard CGE models by the Partnership for Economic Policy (PEP) and the International Food Policy Research Institute (IFPRI) have been directly applied or modified.

In this study, we extend the PEP-1-1 standard single-country static CGE model by Decaluwé, Lemelin, Robichaud, and Maisonnave (2013). Our extensions to the model include (i) the integration of the ethanol sector based on maize, cassava (chips), sugarcane, and molasses (ii) the introduction of a by-product sector (molasses), (iii) the inclusion of factor income from abroad, and (iv) the blending equation (please see Appendix A). The original SAM consists of 186 activities and commodities, which we aggregate into 34 activities and commodities, including the new sectors. Some model parameters are directly calibrated from the SAM, while others (elasticity parameters) are obtained from the literature. The latter are presented in Table A.2 of Appendix A.

The production structure is presented in Fig. A.1, Appendix A. At the top of every production activity, a Leontief production function combines aggregate intermediate inputs and total value-added in fixed proportions. Except for the ethanol collecting and blending sectors, the aggregate intermediate in the rest of the sectors is also a Leontief function of individual intermediate inputs. Total value-added is a constant elasticity of substitution (CES) function of the capital-land and the labor composites. At the bottom of each nest, components of the capital-land composite are also governed by a CES, and so are the components of the labor composite. Profits are maximized when each factor's marginal product equals its price.

Labor is disaggregated into unskilled (incomplete primary), semi-skilled (completed primary), skilled (completed secondary), and highly skilled (completed tertiary). This categorization includes rural and urban for both male and female groups; thus, a total of 16 labor categories. In the original SAM, land is merged with agricultural capital. We extracted it from total agricultural capital, for only the crop sectors, using a share of 75%, which we derived from the 2013 Uganda SAM by Randriamamonjy and Thurlow (2017).

Each feedstock produces a corresponding ethanol type. Both the ethanol-collecting sector (Ethanol) and the blending sector (Blend) have no value-added, and their intermediate inputs are governed by a CES. The Ethanol sector combines all ethanol types as perfect substitutes using a CES function (Eq. (1)). The demand for each type is derived from the first-order conditions for cost minimization, subject to the CES technology (Eq. (2)). Similarly, the Blend sector combines total ethanol and gasoline in a CES function as perfect substitutes (Eq. (3)). The demand for each fuel is a result of cost minimization (Eq. (4)). Please note that for the model to converge, the share of biofuels should vary in the production of the blended product (Woltjer & Kuiper, 2014). To achieve an equal offset of gasoline by the volume of ethanol, we treat the two fuels as perfect substitutes. We simply fix the mandated share exogenously, and consumers make no choice. Moreover, a consumption subsidy equates the purchaser prices for the two fuels.

$$TEHTD_{ec} = B^{ed}_{ec}\left[\sum_{et} \beta^{ed}_{et,ec}\, ETHD_{et,ec}^{-\rho^{ed}_{ec}}\right]^{-\frac{1}{\rho^{ed}_{ec}}} \quad (1)$$

$$ETHD_{et,ed} = \left[\frac{\beta^{ed}_{et,ec}P(ec)}{P(et,ec)}\right]\ \left(B^{ed}_{ec}\right)^{\sigma^{ed}_{ec}-1}\ TEHTD_{ec} \quad (2)$$

$$BLD_{b} = B^{fd}_{b}\left[\sum_{f} \beta^{fd}_{f,b}\, FUEL_{f,b}^{-\rho^{fd}_{b}}\right]^{-\frac{1}{\rho^{fd}_{b}}} \quad (3)$$

$$FUEL_{f,b} = \left[\frac{\beta^{fd}_{f,b}P(b)}{P(f,b)}\right]\ \left(B^{fd}_{b}\right)^{\sigma^{fd}_{b}-1}\ BLD_{b} \quad (4)$$

$$-1 < \rho^{ed}_{ec} < \infty; -1 < \rho^{fd}_{b} < \infty; 0 < \sigma^{ed}_{ec} < \infty; 0 < \sigma^{fd}_{b} < \infty$$

In the above equations $TEHTD_{ec}$ is total ethanol in the Ethanol sector (ec), $ETHD_{et,\,ec}$ the type of ethanol (et) into sector (ec), B^{ed}_{ec} the scale parameter, $\beta^{ed}_{et,\,ec}$ the share parameter, ρ^{ed}_{ec} the elasticity parameter, σ^{ed}_{ec} the elasticity of substitution parameter, $P(et,ec)$ the price for ethanol type (et) into ethanol sector (ec), and $P(ec)$ is the intermediate consumption price index for the Ethanol sector. For the blending sector, BLD_b is total blended fuel, $FUEL_{f,\,b}$ the fuel (f) (ethanol or gasoline) entering the blend sector (b), B^{fd}_{b} the scale parameter, $\beta^{fd}_{f,\,b}$ the share parameter, ρ^{fd}_{b} the elasticity parameter, σ^{fd}_{b} the elasticity of substitution parameter, $P(f,b)$ the price of the individual fuel (f) into the blend sector (b), and $P(b)$ is the intermediate consumption price index for the Blend sector.

Activities can produce more than one commodity, and the output from an individual sector is aggregated using a constant elasticity of transformation (CET) function, except for the by-products (molasses). Domestic output is directed to the domestic and export markets under the assumption of imperfect substitutability represented by a CET function. Domestic demand is made up of household consumption demand, public demand, investment demand, intermediate demand, and the demand for margin services. The imperfect substitutability between domestic and imported commodities is captured by a CES function for Armington aggregation. A small country-hypothesis regarding exports and imports is adopted; hence, their world market prices are exogenous. Nonetheless, an exporter can increase his world market share depending on the competitiveness of the free-on-board price relative to the world price, and on the price elasticity of demand for the exports.

Our household sector consists of 32 representative types grouped according to the Central, Eastern, Northern, and Western regions of Uganda. These groupings are further categorized into rural and urban under four income quintiles. The disaggregation allows for a richer analysis of the income distribution and welfare effects. Household income comprises of factor payments and transfers from firms, other households, the government, and the rest of the world. This is spent on consumption, taxes, savings, and transfers (locally and abroad). The consumption demand functions are linear expenditure systems derived from the maximization of a Stone-Geary utility function, subject to a consumption expenditure constraint. Because of the mandate and the consumption subsidy, consumption of the blended fuel is not different from consumption of conventional fuel.[3]

Under the factor market closure, land is underutilized and mobile in agriculture.[4] We also assume unemployment in the labor market. The supply of these factors is, therefore, endogenized, while the rent and the wage are fixed. This is a common closure in studies on Uganda, intended to capture idle land and unemployment in the economy (Shinyekwa & Mawejje, 2013). All the unskilled labor can move freely

[3] Consumers can only buy the blended product at a price not higher than that of the conventional fuel (gasoline).

[4] We are using agriculture to refer to only the crop sectors. It therefore excludes fishing, forestry and animal husbandry.

in the agriculture, firewood, charcoal, and the molasses sectors (hereafter "the rural sectors"), but it is immobile in the rest of the sectors (hereafter "the urban sectors").

Capital is fixed in supply and fully employed. It is sector-specific in agriculture, but mobile across the non-agricultural sectors. Although the capital mobility assumption may not be suitable in this context, we could not invoke the sector-specific assumption because we are introducing new sectors while holding the supply of capital constant. We recognize the limitations of capital transfers for project financing in developing countries (United Nations Conference on Trade and Development, 2018). Moreover, the current production proposals are dependent on installed capacity, and from our interviews, producers claim to have this capacity in place. Therefore, like Boccanfuso et al. (2018), we assume that expansion of the ethanol sector is generated using existing capital in the economy; for example, the annexed distilleries that are already in operation.

For the macroeconomic closure, foreign savings are fixed and the exchange rate is endogenized to clear any imbalances on the current account. This assumption is appropriate since Uganda runs a flexible exchange rate system. We use the GDP deflator as the model numeraire. The savings-investment balances are investment-driven, with savings as the endogenous variable. Total investment is the sum of savings by households, firms, government, and foreign borrowings. It is made up of both gross fixed capital formation and changes in stocks, with the former endogenous and the latter fixed. Government savings is a flexible residual between revenues and expenditures, and all tax (subsidy) rates are fixed.

Modeling ethanol production

Details of all the calculations in this section are presented in Appendix B. Currently, companies produce ENA from maize, cassava, and molasses as they await the government to enforce mandatory consumption and to provide other incentives. This information was obtained from our field visits, and it is the basis for the SAM adjustments. We use maize, cassava, sugarcane, and molasses as the feedstocks. Each feedstock is supplied by its respective sector, except for molasses, which does not exist in the original SAM. We introduce a molasses sector without production of its own, but its output is the by-product molasses from the sugar industry.

From our interviews with the experts in the sugar industry and UBOS, the value of molasses is captured in the value of sugar. We use data on sugar production and the corresponding amount of molasses. Using the monetary values of both, we derive the share of molasses as 2.7% of the value of sugar. We use this to calculate the value of by-product molasses from the sugar industry. It enters the molasses sector through a Leontief functional relationship. The distribution of the final output is that: 86% goes to the 'food processing' sector, 13% to the 'Spirits-alcohol' sector that makes alcoholic beverages, and 1% enters the 'prepared animal feed' sector.[5] The molasses-ethanol sector only creates an additional demand determined by the input coefficient.

Arndt, Benfica, et al. (2010), Arndt, et al (2010), and Hartley et al. (2018) treat biofuels as a tradable sector, and the entire production is exported. We take a different approach and assume production for domestic use only. This is intended to determine the impact of reducing gasoline imports on the import tax revenues and the trade balance. Since ethanol in our analysis is for transport, we disaggregate the gasoline sector from the aggregate petroleum sector using the share of gasoline (44%) in the total petroleum products imports. The technical structure of this sector is derived from the petroleum sector. Please note that in Uganda, all the gasoline is primarily used for transport.

We follow the latent approach by introducing tiny amounts of ethanol in the SAM (see Taheripour et al., 2017). In this case, ethanol output is practically zero in the base year because it is more expensive than gasoline, and there is a lack of effective demand. Production occurs only when the sector becomes competitive through government interventions and market incentives. The technical coefficients for the four ethanol sub-sectors are from Zhou and Kojima (2011). We adjusted them to reflect local costs, and the final technical structure is provided in Table B.2. Based on the data from the ethanol-producing companies, the basic price for undenatured ethanol was about USD 0.86 per liter, which is equivalent to Ush. 3000 in 2016/17 prices. We adopt this price as the production cost per liter of fuel-grade ethanol. To avoid the zero problem, we introduce a small quantity of about 0.676 million liters for each ethanol type in the base year. We multiply this quantity by the production cost of Ush. 3000 per liter to obtain a nominal value of Ush. 2.03billion for each.

We use an ad valorem consumption subsidy to make ethanol competitive. The purchaser prices calculated from the SAM are 2.30[6] and 1.90 for ethanol and gasoline, respectively. We use the price for gasoline as the reference price and derive a subsidy rate of about 33% per liter of ethanol. The subsidy equates the two prices and makes fuel-ethanol competitive. To maintain a neutral government budget, we impose an initial corresponding tax rate of 0.22% per liter of gasoline, which is quite small, because the large volume of gasoline provides a broader tax base.[7] Finally, we balance the SAM using the cross-entropy method by Lemelin, Fofana, and Cockburn (2013).

Definition of the baseline model and policy simulations

The baseline model depicts the structure of Uganda's economy with almost zero fuel-grade ethanol. We first run the model without any simulations to make sure it replicates the base year equilibrium. For the simulations, we first identify the volume of gasoline in the base year. The imported volume was approximately 818 million liters (MEMD, 2016). Some of it, however, is re-exported. We calculate a share of 14% as re-exports using the values in the SAM. The remaining 86% (about 703 million liters) makes up domestic consumption. The required ethanol at a 10% blending rate is, therefore, 70.3 million liters. We multiply this volume by the basic price per liter (Ush. 3000) to obtain a nominal value of Ush. 211.05 billion, which we use in all our simulations. All the calculations are provided in Table B.2 Appendix B.

Scenarios and simulations description

We came up with four scenarios, and each is based on the production of ethanol worth Ush. 211.05 billion. In all the scenarios, unless where it is explicitly stated, maize, cassava, and sugarcane ethanol contribute an equal share (33.3%) to the total production.

Scenario 1. This scenario maintains the baseline closures. There is unemployment in the labor market. Skilled labor is mobile across all sectors, while unskilled labor can only move freely across the rural sectors. Land is underutilized and mobile within agriculture. Capital is mobile across the non-agricultural sectors but sector-specific in agriculture.

Scenario 2. In this scenario, we have all the assumptions in scenario 1, except that land is fully employed. It allows us to investigate the impacts of land constraints.

Scenario 3. Under this scenario, the share of sugarcane ethanol in total production is met by molasses. We test the likely outcome of using

[5] This distribution follows closely the initial distribution of sugar and additional explanation is presented in Appendix B.

[6] Purchaser prices include commodity taxes (subsidies) and trade margins. The trade margins, and VAT on ethanol are adopted from the gasoline sector. We, however, introduce a product tax of 80% which is the rate on undenatured ethanol according to the current tax regime.

[7] Please note that the subsidy and tax rates are ad valorem and endogenous; they are allowed to adjust in all simulations.

by-product molasses from the sugar industry. This scenario is crucial because molasses is currently used to produce ENA, and fuel-ethanol is anticipated to come from the same by-product molasses. The purpose is to verify the envisaged benefits, considering that this feedstock is already an input in other activities.

Scenario 4. We assume total production from one feedstock at a time and compare the findings for all ethanol types. We also make a comparison with the main scenario (scenario 1), which assumes an average of feedstocks.

Sensitivity analysis. We carry out a sensitivity analysis to test the robustness of the model by choosing different elasticity of substitution parameters between capital and labor. We also run one test using an unbalanced budget, and another where all the factors of production are mobile and fixed in supply.

Results and discussion

In this section, we present and discuss the findings. All the results are reported as percentage deviations from the base year equilibrium values unless otherwise stated. Our analysis is based on a static model that does not incorporate dynamic effects; hence, the growth effects are not exhaustively captured. The results are, therefore, only suggestive and simply shed light on the possible implications.

Scenario 1

In this scenario, land is underutilized and mobile. Capital is sector-specific in agriculture but mobile in other sectors, and we assume unemployment in the labor market.

Impacts on output, factor employment, and prices

The ethanol sector creates new demand for the crops that serve as feedstocks. This raises the production and prices of these crops, which leads to growth in revenues. Since agricultural capital is sector-specific, the feedstock sectors draw in more land and labor to meet the growing demand. In Table 4.1 under S1 (for scenario 1), employment of land and labor rises in the maize, cassava, and sugarcane sectors, while it declines elsewhere. Because capital is sector-specific, it becomes relatively scarce compared to the supply of land and labor. This raises its marginal product and rental rate in expanding sectors. The labor wage and rent on land remain constant because of the unemployment assumption and the existence of underutilized land (see Table 4.1). Overall, total agricultural output increases. Table 4.2 (S1) shows an expansion of maize and cassava production by over 1%. Sugarcane activity increases with a higher percentage because it has the lowest ethanol conversion rate compared to maize and cassava.[8] The sectors with declining activities experience a fall in output, prices, and capital rental rates.

Sugar activity contracts not only because of capital reallocation but also because of the competition for sugarcane from the ethanol sector. The higher rental rates on capital, the new demand for feedstocks, and the decline in output of other sectors exert an upward pressure on commodity prices. Ethanol prices also rise despite the subsidy. The price of gasoline increases due to the counter-financing tax, and so does the final fuel price. The CPI rises, and consumption of most commodities falls marginally.

Our findings are consistent with those by (Wianwiwat & Asafu-Adjaye, 2013). In their study, land reallocates to the feedstock sectors; in the short-run, it increases by 3.3 and 33% in the cassava and sugarcane sectors, respectively. They also show that as the demand for ethanol rises, the prices of inputs, such as molasses, cassava, and tapioca chips increase, but the adverse effects on the food sector are minimal.

Impacts on household income, consumption, and welfare

The growth of mainly capital income and revenue in the feedstock sectors raises household disposable income. This occurs mostly for the rural households (see data series S1 in Fig. 4.1). The percentage change in income ranges from 0.01 to 0.10%. Household welfare, which is measured by equivalent variation (EV), declines across all households (Fig. 4.2). This is mainly because of the tax burden from the counter-financing tax on gasoline. The pattern of EV follows the change in the household real consumption budget (not reported), and the financing tax on gasoline seems more progressive in this context. Fig. 4.2 can be compared with Fig. C.1 in Appendix C under the unbalanced budget case, which excludes the effect of the financing tax.

In the study by Al-Riffai and Laborde (2010), biofuels production enhances rural household income. Arndt, Benfica, et al. (2010) and Arndt, Pauw, and Thurlow (2010) report a potential reduction in poverty levels arising from distributional income effects.

Impacts on the trade balance and economic growth

Exports fall and imports rise across all commodities; the period is too short to allow full adjustment in domestic production. Exports of maize and cassava decline as their imports rise to meet the increasing demand. Sugarcane exports, however, remain almost constant while the imports rise markedly (Table 4.2). As reflected in their respective volume indices, the decrease in total imports exceeds the fall in total exports (Table 4.3). The impact on total imports is exacerbated by the substantial reduction in gasoline. As a response to these movements in the trade balance, the real exchange rate appreciates by 0.29% (see Table 4.3). If export supply could be maintained, this outcome portrays prospects for an improved trade balance.

Gasoline is one of the heavily taxed commodities; hence, its decline reduces import tax revenues. However, since other commodity taxes like value-added and the sales tax increase at the same time, total tax revenue rises. As a result, the change in government income and savings is positive. We, however, notice that this outcome is, to some extent, dependent on maintaining some taxes on ethanol. Overall, the economy grows with real GDP expanding by 0.05%.

Scenario 2

In this scenario, land is fully employed and mobile. Capital is still sector-specific in agriculture but mobile in other sectors, and we assume unemployment in the labor market.

The results from this scenario, referred to as S2 (for scenario 2), are presented with the results from scenario 1 in the same tables and figures. Because both land and capital are fixed in supply, land use increases at a slower pace, while labor demand grows faster to generate the required output. Similar to scenario 1, sector-specificity of capital drives up its marginal product and the rental rate in the feedstock sectors. The sectors whose activity and prices decline record negative rental rates on capital. The growth in household income is slower, and it drops for some households while welfare deteriorates across all.

The reduction in exports and the increase in imports are higher than in scenario 1. Government revenue and savings rise, but real GDP declines. The rise in the cost of production and commodity prices is higher, and the increase in the CPI of 0.12 substantiates this (see Table 4.3). Therefore, in the absence of surplus land or productivity enhancement, short-run benefits may be limited. To a larger extent, we attribute the growth in scenario 1 to the existence of idle land.

Scenario 3

In this scenario, the share of sugarcane ethanol in total ethanol production is met by molasses ethanol.

[8] A lower conversion rate means more sugarcane input to produce a given volume of ethanol. Furthermore, the initial base year values are relatively small, hence the large percentage deviations.

Table 4.1
Percentage change in factor demand and rental rate on capital.

	Scenario 1				Scenario 2			
	Land demand	Capital demand	Rate on capital[b]	Labor demand	Land demand	Capital demand	Rate on capital[b]	Labor demand
Maize	2.01	[a]	1.70	3.31	1.62	[a]	2.09	3.43
Cassava	1.80	[a]	1.52	2.96	1.51	[a]	2.00	3.25
Sugarcane	12.58	[a]	11.55	22.20	12.23	[a]	11.99	22.44
Grain seeds	−0.07	[a]	−0.06	−0.11	−0.47	[a]	0.32	−0.02
Other agric	−0.28	[a]	−0.23	−0.45	−1.05	[a]	−0.16	−0.96

[a] Not applicable because capital is activity-specific in agriculture; hence, its demand does not change.
[b] Refers to the sectoral rental rate of composite capital, which combines land and capital. It declines by 0.06% and 0.14% under S1 and S2, respectively, in the sectors where capital is mobile (not shown). The higher percentage changes in the sugarcane variables are a result of smaller initial values. Other agric. includes all the cash crops like tea, coffee, cotton, vanilla, etc.

The findings in this section are summarized in Table 4.4. A simulation of an average of maize, cassava, and molasses ethanol generates errors if we set no limit to the subsidy budget. We, therefore, fix the subsidy budget for maize and cassava ethanol to their levels in scenario 1 (Ush.28 billion for each). Molasses ethanol adopts the budget for sugarcane ethanol (Ush.32 billion). Only about 52 million liters of the required 70.3 million liters are realized, with molasses ethanol contributing just 10% of this volume. The new demand from the ethanol sector puts an upward pressure on the price of molasses, and it escalates by over 300%. This high price is transmitted to the molasses ethanol price, and it erodes the subsidy budget (by raising the subsidy rate). There are reasons that explain this. First, molasses is currently used to produce products such as ENA, whose purchaser price is as high as USD.1.80 per liter. Second, the recovery rate for molasses is only 4% compared to that of sugar that ranges between 9 and 11% (Ministry of Tourism, Trade and Industry MTTI (2010). Finally, molasses is extremely cheap compared to sugar. Therefore, the extent to which the demand for molasses prompts the growth in sugar production will be limited. It is untenable for a cheap product (molasses) to drive the growth in an expensive primary product (sugar) in order to generate more by-products (molasses).

From the simulation, the possible additional molasses induces a higher production of sugarcane and sugar. The sugarcane and sugar sectors draw in more resources, and their output increases significantly. Nevertheless, total value-added and real GDP rise moderately.

Sugar production increases and saturates the domestic market, leading to over 20% growth in its exports. This attenuates the decline in total exports. It is also a boon for consumers because of the price fall and the increase in consumption. Nonetheless, the 'processed-food,' 'animal feed,' and the 'spirit and alcohol' sectors that use molasses are

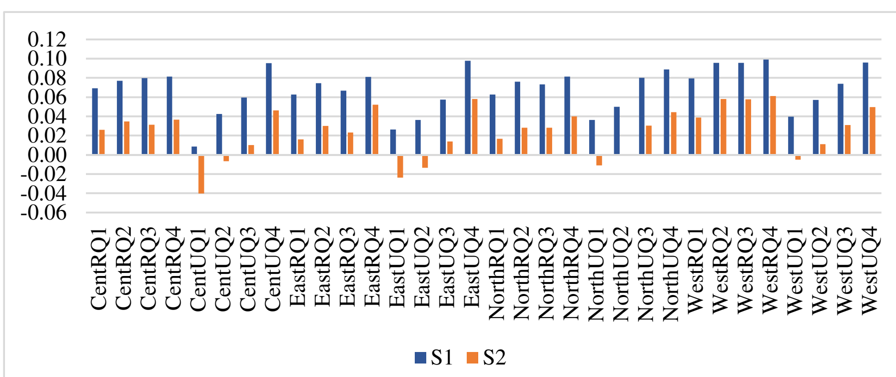

Fig. 4.1. Percentage change in household disposable income. The horizontal axis plots households for the central, eastern, northern and western regions; with R and U representing rural and urban, respectively. The Qs from 1 to 4 represent the four income quintiles. S1 and S2 are scenario 1 and 2, respectively.

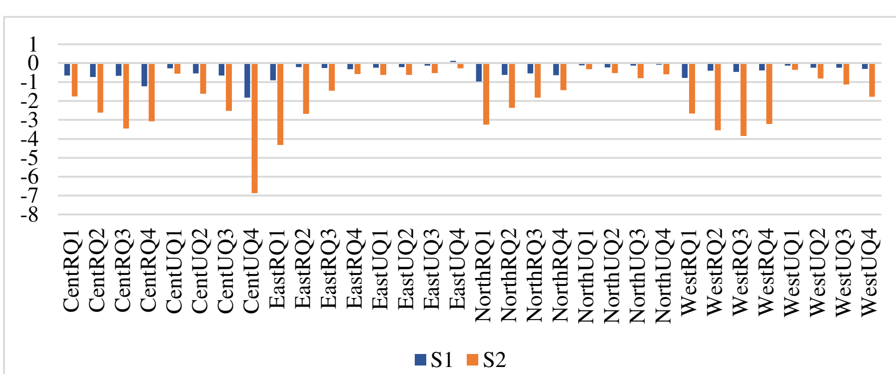

Fig. 4.2. Change in household welfare measured by equivalent variation. The change in equivalent variations is in absolute terms (billions of Uganda shillings).

Table 4.2
Percentage change in output, prices, and consumption.

	Scenario 1					Scenario 2				
	Output	Exports	Imports	Price	Consumption	Output	Exports	Imports	Price	Consumption
Maize	1.73	−1.45	11.59	1.54	−0.72	1.50	−2.26	13.35	1.87	−0.92
Cassava	1.37	−1.82	8.98	1.27	−0.59	1.17	−2.83	10.89	1.66	−0.82
Sugarcane	14.07	0.00	58.18	6.55	−2.94	14.00	−0.50	59.87	6.79	−3.09
Grain-seeds	−0.06	−0.39	0.25	−0.04	0.05	−0.32	−1.27	0.65	0.24	−0.13
Other agric	−0.24	−0.29	0.21	−0.13	0.09	−0.81	−0.94	0.25	−0.07	0.01
Animal farm	−0.04	−0.38	0.29	−0.02	0.04	−0.08	−0.27	0.10	−0.09	0.03
Processed food	−0.26	−1.13	0.67	0.22	−0.11	−0.33	−1.23	0.65	0.24	−0.19
Animal feed	−0.21	−0.88	0.06	0.16	–	−0.24	−0.87	0.01	0.14	–
Sugar	−0.79	−1.46	0.54	0.13	−0.06	−0.84	−1.51	0.48	0.13	−0.12
Spirits + alcohol	−0.15	−0.75	0.46	0.08	−0.01	−0.19	−0.75	0.40	0.06	−0.06
Transport	−0.39	−1.03	0.75	0.15	−0.06	−0.36	−0.91	0.63	0.11	−0.09
Gasoline			−16.73	4.48				−16.73	4.50	
Blended fuel				4.33	−1.90				4.34	−1.95
Molasses				49.83					49.38	
Sugarcane ethanol				1.29					1.30	
Cassava ethanol				1.29					1.30	
Maize ethanol				1.29					1.30	

Table 4.3
Percentage change in key macroeconomic variables.

	Scenario 1	Scenario 2
Real exchange rate	−0.29	−0.3
Import volume index	−0.94	−0.98
Export volume index	−0.70	−0.77
Agricultural output	0.45	0.15
Real GDP at market price	0.05	−0.02
Total value-added	0.07	0.02
Consumer price index (CPI)	0.10	0.12
Government income	0.70	0.64
Government saving	13.57	12.37
Import tax revenue	−0.37	−0.43
Total revenue from all product taxes	1.19	1.14
Total subsidies	89[a]	90[a]

[a] Refers to absolute values of the subsidy budget in billions of Uganda shillings.

significantly affected. Government income and savings increase, and the pronounced growth in the sugarcane and sugar activities generates a higher growth in income for most households (Fig. 4.3). Welfare improves for just a few rural households (Fig. 4.4).

Al-Riffai and Laborde (2010) also find that using molasses would be costly, especially if it is already efficiently used in other sectors. However, contrary to our findings, their change in household income and GDP is negative. Our case exhibits strong growth effects from the sugarcane, sugar, molasses, and the ethanol sectors. When we assume full employment of factor inputs, which is applied in their analysis, real GDP declines by 0.001%. Nonetheless, income still rises for the rural households (Fig. C.2 Appendix C), and the impact on welfare remains practically the same (Fig. C.3 Appendix C). Since we use a similar model, the divergence could be attributed to differences in elasticity parameters, the model numeraire, the data, or the general model specification.

Please note that the above findings are conditional on the willingness of the government to offer a higher subsidy rate for molasses ethanol, but this may be economically infeasible.

Table 4.4
Percentage change in factor demand, capital rent, output and price (scenario 3).

	Land demand	Capital demand	Labor demand	Capital rate	Output	Exports	Imports	Price	Consumption
Maize	1.76	[a]	2.90	1.49	1.52	−1.49	10.78	1.37	−0.63
Cassava	1.62	[a]	2.67	1.37	1.24	−1.84	8.54	1.14	−0.52
Sugarcane	10.26	[a]	17.62	9.25	11.43	−0.05	46.00	5.27	−2.40
Grain seeds	−0.17	[a]	−0.27	−0.14	−0.14	−0.50	0.18	−0.10	0.07
Other agric	−0.40	[a]	−0.64	−0.33	−0.34	−0.40	0.11	−0.21	0.14
Animal farm		−0.28	−0.05	−0.08	−0.26	−0.74	0.19	−0.03	0.03
Processed food		−0.92	−0.19	"	−0.77	−2.76	1.44	0.69	−0.47
Animal feed		−0.55	−0.05	"	−0.52	−1.54	−0.12	0.26	–
Sugar		19.95	2.27	"	12.05	20.65	−4.40	−3.77	2.86
Spirits + alcohol		−0.92	−0.11	"	−0.63	−2.20	1.07	0.44	−0.29
Transport					−0.47	−1.19	0.79	0.11	−0.06
Gasoline							−12.26	4.17	–
Blend								4.06	−1.82
Molasses								338	
Molasses-ethanol								2.30	
Cassava-ethanol								1.04	
Maize-ethanol								1.03	

Exchange rate	Import volume index	Export volume index	Real GDP	CPI	Govt income	Import tax revenue	Total product tax revenue	Agricultural output	Total value-added
−0.35	−0.65	−0.49	0.02	0.09	0.56	−0.42	0.97	0.31	0.04

[a] Not available because agricultural capital is immobile.

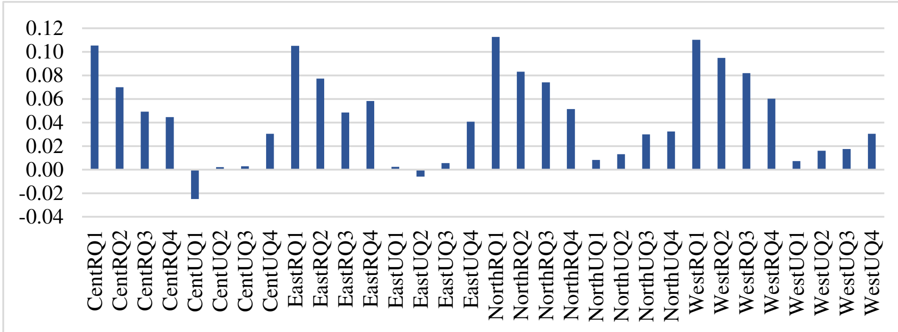

Fig. 4.3. Percentage change in household disposable income.

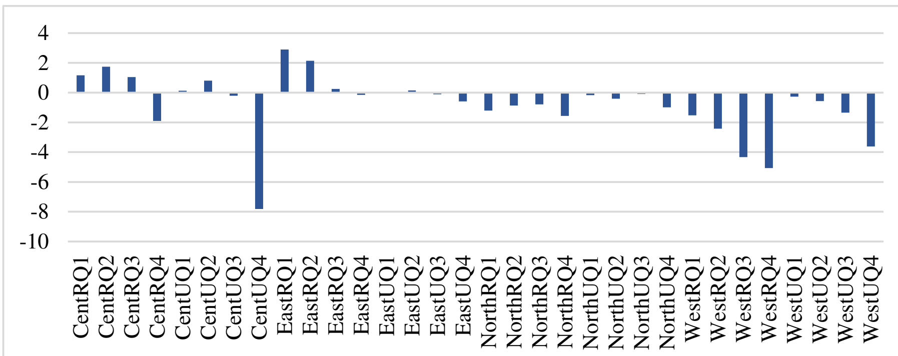

Fig. 4.4. Change in equivalent variation.

Scenario 4

In this scenario, we assume total ethanol is produced from one feedstock at a time. Based on the results from scenario 3, we decided to exclude molasses. The findings are reported in Table 4.5. Both sugarcane and maize seem more promising. They cause higher growth in agricultural output and GDP than cassava does. Sugarcane generates the highest growth in income for all households, but this is moderate under maize, and it declines for some households under cassava (Fig. 4.5).

Sugarcane ethanol takes the highest subsidy budget. This is because it has a lower conversion rate, implying more sugarcane input. This raises the demand and price of sugarcane. The higher price for sugarcane is transmitted to the ethanol price, and it explains why we have the highest increase in the CPI.

Column D presents the results from scenario 1, in which each feedstock contributes an equal share to total production. Despite a slower growth in GDP, a comparison with all the other cases in columns A, B, and C, reveals that a combination of feedstocks is likely to avert price escalations while achieving growth. We, accordingly, concur with the NEMA (2010) report, which supports the hypothesis that a combination of feedstocks would be more efficient and sustainable.

Sensitivity analysis results

Most of the test results under the various elasticity parameters in columns A, B, and C are close to our main findings (see Table 4.6). We also present in column D, a case of an unbalanced government budget. In this case, the growth in GDP is similar to scenario 1, but government income declines. This test allows us to identify the net welfare effect of ethanol production. We observe that in the absence of a financing tax, most rural households have their welfare enhanced. It, however,

Table 4.5
Percentage change in key macroeconomic variables – single feedstock case.

	A	B	C	D
	100% sugarcane ethanol	100% cassava ethanol	100% maize ethanol	Equal share (scenario 1)
Real exchange rate	−0.28	−0.34	−0.28	−0.29
Import volume index	−0.94	−0.96	−0.96	−0.94
Export volume index	−0.69	−0.73	−0.73	−0.70
Agricultural output	0.62	0.29	0.49	0.45
Real GDP at market price	0.09	0.01	0.05	0.05
Total value added	0.11	0.04	0.07	0.07
CPI	0.14	0.11	0.11	0.10
Gov't income	0.94	0.69	0.74	0.70
Tot. product taxes	1.61	1.18	1.27	1.19
Total subsidies	135[a]	94[a]	99[a]	89[a]
% Change in production from the base equilibrium values				
Maize	−0.15	−0.19	5.57	1.73
Cassava	−0.04	4.25	−0.07	1.37
Sugarcane	44.97	−0.05	−0.01	14.07
Grain seeds	−0.03	−0.09	−0.06	−0.06
Other agriculture	−0.18	−0.29	−0.21	−0.24
Animal farm	−0.05	−0.04	−0.05	−0.04

The size of each budget is determined by the rate of the price increase for the respective feedstock; sugarcane has the fastest growth in price. Column D presents results from scenario 1, in which the three feedstocks contribute an equal share to total ethanol.
[a] Refers to absolute values in billions of Uganda shillings.

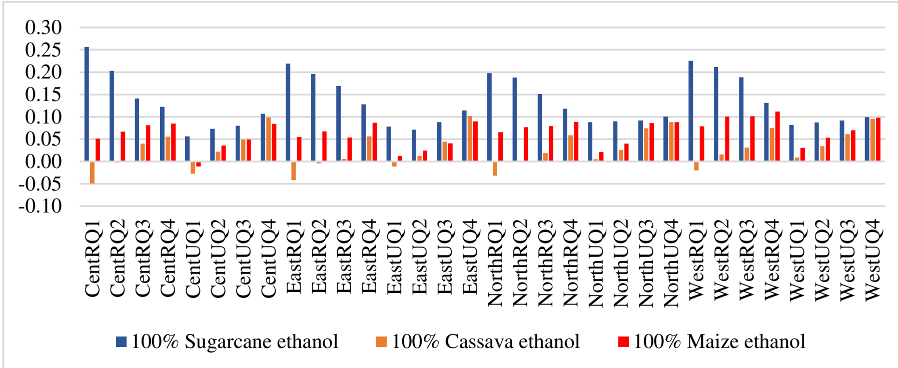

Fig. 4.5. Change in disposable income with total production from one feedstock.

remains constant for many urban households and the rural poor. We attribute this outcome to the increase in food prices, which erodes households' purchasing power, despite the growth in income (see Fig. C.1 in Appendix C).

In Column E, all the factors of production are mobile and fixed in supply. Household income and welfare decline (Figs. C.4 and C.5 in Appendix C). A comparison of these findings with those from scenario 1 shows that without productivity improvement, if all factor inputs are fixed in supply, ethanol production may negatively affect both sectoral and total output.

Conclusion and policy implications

We use a static CGE model to assess the economic impacts of ethanol production by simulating a 10% blending mandate. We introduce an ethanol sector based on maize, cassava, sugarcane, and molasses. To address our main research question, we specifically examine (i) the impacts on employment, output, and prices, (ii) the impacts on household income and welfare, (iii) the effects on the trade balance, government income, and overall economic growth. We also evaluate the suitability of the feedstocks. In our main scenario (scenario 1), land is underutilized and mobile in agriculture, and labor faces unemployment. Capital is mobile in the non-agricultural sectors but sector-specific in agriculture. We find that factor employment and output increase in the feedstock and ethanol sub-sectors, but they decline in most of the remaining sectors. Prices of most commodities rise, and their consumption drops. Income grows mostly for the rural households, while welfare declines across all. Without a counter-financing tax, the majority of rural households have their welfare enhanced. It, however, remains constant for many urban households and the rural poor. Despite these effects, our results strongly suggest potential growth effects from ethanol. It might, however, require the government to synergize ethanol policies with other pro-poor policies such as encouraging micro-distilleries and the pursuance of an integrated food-fuel system. The growth effects are also conditional on surplus land, which is, to some extent, a valid case in Uganda and most developing countries. The available resources can, therefore, kick off an ethanol program.

If export supply could be maintained, a reduction in gasoline imports presents prospects for an improved trade balance. Although the concern for the loss in import tax revenues is valid, government income rises, and real GDP grows moderately.

Both sugarcane and maize result in higher growth than cassava. The envisaged benefits of using molasses from the sugar industry may be overstated. Its price rises faster and affects other sectors using it as an input. We recommend the use of by-product molasses to be augmented by the direct use of sugarcane juice or additional molasses from jaggery mills. It would also be prudent to use an average of feedstocks, to avoid escalating prices. This would also balance the distribution of income because the cultivation of crops varies with ecological regions.

Our analysis is based on a static model; thus, further research in a dynamic CGE framework would provide additional insight. We also based our findings on a consumption subsidy; therefore, investigations of different policy incentives would also be useful.

Table 4.6
Results from the sensitivity analysis tests.

	A	B	C	D	E
	Balanced	Balanced	Balanced	Balanced	Unbalanced
EOS1	0.9	1.5	1.8	1.05	Full
EOS2	0.4	0.8	0.9	0.6	Employment
EOS3	0.3	0.3	0.4	0.3	(Uses EOS of D)
% Change in macroeconomic variables					
Real exchange rate	−0.29	−0.29	−0.28	−0.30	−0.18
Import volume index	−0.93	−0.94	−0.94	−0.94	−1.08
Export volume index	−0.7	−0.71	−0.71	−0.71	−0.87
Agricultural output	0.45	0.45	0.47	0.42	0.07
Real GDP at market price	0.06	0.05	0.06	0.05	−0.01
Total value added	0.08	0.07	0.08	0.07	0.00
CPI	0.10	0.10	0.10	(0.00)	0.09
Gov't income	0.70	0.69	0.69	−0.13	0.62
Tot. product taxes	1.20	1.18	1.18	−0.27	1.11
% Change in production					
Maize	1.72	1.76	1.92	1.69	2.60
Cassava	1.37	1.38	1.49	1.38	1.81
Sugarcane	14.04	14.16	14.32	13.96	15.02
Grain seeds	−0.06	−0.06	−0.06	−0.07	−0.19
Other agriculture	−0.23	−0.25	−0.31	−0.36	−3.31
Animal farm	−0.04	−0.04	−0.02	−0.07	−0.03

Balanced means that the subsidy is counter-financed by the tax on gasoline.
EOS stands for the elasticity of substitution.
EOS1 is for substitution between aggregate capital and aggregate labor.
EOS2 is used to substitute the different labor types. The same would apply to capital substitution in the non-agricultural sectors if there were more than one capital type.
EOS3 is for substitution between capital and land in agriculture.

Declaration of competing interest

We declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2020.10.003.

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Paper II

Assessment of alternative policy instruments to promote biofuels in developing countries

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Abstract

This study evaluates possible policy instruments to incentivize ethanol production in low-income countries in a general equilibrium framework. We assess a feedstock production subsidy, an ethanol consumption subsidy, a combination of the two subsidies, and a gasoline tax. We apply the size of the subsidy budget and the impacts on agricultural output, prices, real GDP, government income, the trade balance, household income, and overall welfare as the performance indicators. The ethanol consumption subsidy takes the smallest budget and performs reasonably well, but it exerts upward pressure on food prices. On the other hand, the feedstock subsidy generates substantial gains across all indicators but requires a large resource budget. Despite the high government income from the gasoline tax policy, it also raises commodity prices and erodes household welfare. We find a two-part instrument of a feedstock and ethanol consumption subsidy as the most suitable. Finally, the presence of sector-specific capital in agriculture impairs the effect of the subsidies, raising the taxpayers' financing burden.

Keywords: CGE, policy, subsidy, incentives, ethanol, development, welfare

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1.0 Introduction

Biofuels have noticeable advantages, but it is also true that they are less competitive relative to fossil fuels in terms of production costs (Hill et al.,2006) and energy content. Additionally, production may lead to unintended socio-economic and environmental risks if not well managed. Besides, consumer acceptance also matters regarding fuel preferences (Moula, Nyári & Bartel, 2017). In this regard, government policies and support become indispensable in ensuring reliable biofuel supplies and steady biofuel markets.

Various policies such as consumption targets and blending mandates, tax reductions and exemptions, subsidies, carbon taxes, biofuels import tariffs, and other environmental standards have been deployed (Brown et al.,2020). Even with higher fossil fuel prices, these policies and active government support lie at the heart of the biofuel development in most countries. For example, the Renewable Fuel Standard (RFS) in the US has guaranteed the biofuel market after the expiration of the Volumetric Ethanol Excise Tax Credit (VEETC. The US farm bill of 2018 continues to provide agricultural support for various crops, including corn [7] (McMinimy et al., 2019). Similarly, Brazil's ethanol industry has thrived on market regulations and incentives under the Proalcohol program, with the development of flex-fuel vehicles[8] , further accelerating biofuel demand (Janda, Kristoufek & Zilberman, 2012). The EU, under the renewable energy directive, set targets for member countries of 10 and 14 percent for energy used in transport to come from renewable sources by 2020 and 2030, respectively (Directive 2009/28/EC & Directive (EU), 2018). Through the Common Agricultural Policy, the EU allowed the planting of feedstocks on set-aside land and extended aid of 45 Euros per hectare for energy crops (Vannini et al., 2006).

The rationale for policies is to correct market failures (Rajagopal & Zilberman, 2008), such as the under-provision of an emission-reducing fuel (ethanol), uncertainty regarding new investments, traffic congestion, and air pollution. However, policy choice is challenging: a single policy may not be effective across all the relevant criteria (Goulder & Parry, 2008). For instance, a policy tool that promotes ethanol may raise the price of food and cause food scarcity (de Gorter & Drabik, 2012; Condon, Klemick, & Wolverton, 2015; Elizondo & Boyd, 2017). In contrast, feedstock subsidies may lower the costs but fail to spur capital investments in the ethanol industry. Based on the polluter-pays principle, an emission tax would be superior to a subsidy that promotes ethanol. However, the tax may be difficult to implement in economies with low household incomes. Likewise, it may fail to address additional market failures that

[7] Corn is the main feedstock for US conventional ethanol
[8] Flex-fuel vehicles can run on a fuel mixture of up 85% anhydrous ethanol-15% gasoline or on 100% pure hydrous ethanol.

hinder investments in the ethanol industry or those associated with consumers' undervaluation of ethanol's environmental benefits (Goulder and Parry, 2008).

Moreover, multiple policies could result in counterintuitive outcomes. For example, in detailed partial equilibrium (PE) analyses, a mandate may subsidize fuel and thus gasoline consumption under a less elastic endogenous gasoline supply, causing a rebound effect [9] (see de Gorter and Just, 2009a, 2010; Drabik, 2011; de Gorter, Drabik, and Just, 2013). Besides, given a fixed blend requirement, an additional tax credit or a subsidy may also increase fuel demand under similar gasoline supply conditions (see de Gorter and Just, 2009a, 2010; Drabik, 2011; de Gorter, Drabik, and Just, 2013). Another line of research is based on the general equilibrium (GE) theory, avoiding the restricted scope of PE models (see Cui, Lapan, Moschini & Cooper, 2011; Lapan & Moschini, 2012; Taheripour & Tyner, 2014; Devadoss and Bayham, 2010). This can capture both the direct and indirect effects, generating further intuition. For example, Taheripour and Tyner (2014) argue and show that a rebound effect may not necessarily occur if the subsidy is counter-financed by a tax. Hence, GE analyses account for the interaction and revenue-recycling effects of the biofuel policies [10], which are crucial in determining the final impact on social welfare (see Devadoss and Bayham, 2010; Cooper & Drabik, 2012; Taheripour & Tyner, 2014).

However, most research on this topic is carried out in developed economies with influence on the world oil and crop markets and have well-functioning factor and commodity markets. But as Azuela and Barroso (2012) asserted, a tailor-made approach should be applied in the choice of policy instruments to promote renewable energy. Moreover, the implication of factor specificity in biofuel policy evaluations is understudied. Specific factors may impair the effectiveness of a policy, causing noteworthy welfare implications (Bento & Jacobsen, 2006). Therefore, we extend the above literature to developing countries and account for sector-specific capital in agriculture. This is crucial because of the interconnectedness of biofuels with the agricultural sector, and it is unrealistic to assume perfect capital markets and capital mobility across sectors in developing countries, especially in the short run. Within this context, this study evaluates the possible policy instruments to promote a nascent ethanol industry amid budget constraints and the goals of energy security, rural development, and emission reduction. We use the case of Uganda to address the following questions. First, what is the appropriate policy for Uganda's ethanol industry

[9] A rebound effect is when the biofuel policy instead increases the consumption of the fossil fuel due to a reducing effect on the fuel cost.

[10] A tax(subsidy) interaction effect occurs when a biofuel tax (subsidy) affects consumers' purchasing power through changes in relative prices. A tax (subsidy) recycling effect is when a tax (subsidy) is financed through a cut (increase) of another tax to balance the government budget.

given the financial constraints? Second, what implications may capital specificity have for the ethanol policy outcomes?

We derive a general equilibrium (GE) analytical model, which we run in a Computable General Equilibrium (CGE) version using GAMS software. The CGE is calibrated to a 2016/17 Uganda Social Accounting Matrix (SAM) with sugarcane, cassava, and maize ethanol. Based on the literature reviewed and the best practices of other countries, we evaluate the feedstock production subsidy, an ethanol consumption subsidy, a combination of both subsidies, and a consumption tax on gasoline. Our policy evaluation is based on the broad criteria of net social benefits, distributional effects, and economic feasibility. Specifically, we compare the size of the subsidy budget and the impacts on agricultural output, prices, total value-added, real GDP, government income, the trade balance, household income, and welfare. Finally, we consider the environmental effect implicitly through changes in fuel consumption.

While a rigorous economic analysis of biofuel policies and their complexity is crucial, we restrict our study to examining possible policies that would maximize benefits. Our main contribution is the extension of the current literature on biofuel policies to developing countries in an evaluation of multiple policy options. Second, considering capital specificity allows us to account for the intersectoral differences between agricultural and other capital. This is relevant since we are analyzing the ethanol industry in the short run. This topic is essential for most developing countries whose biofuel sectors and regulatory frameworks are still in the initial stages. To our knowledge, this is one of the few empirical macroeconomic assessments of ethanol policies in low-income countries and the first in Uganda.

The rest of the paper is organized as follows: Section two presents a brief background of Uganda's biofuel industry and policy framework, while Section three details the analytical model. Section four describes the numerical model and simulations, Section five reports and discusses the results, and six provides the conclusion and policy implications.

2.0 Uganda's biofuel industry and policy framework

Uganda offers an interesting case for biofuels and biofuel policy evaluation. The country has over 64 percent of the working population engaged in agriculture (Uganda Bureau of Statistics (UBOS), 2018). Uganda's climate is conducive for agriculture, and the country has the capacity to produce reasonable volumes of ethanol (Nakamya & Romstad, 2020). Although the current ethanol industry operates on a small scale, mainly processing portable ethanol, our field visits revealed more readiness by investors to process fuel ethanol than biodiesel. In terms of policy, Uganda has already taken preliminary steps to promote biofuels, primarily for economic development and mitigation of climate change. This is evidenced in the Uganda Energy Policy of 2002, the Renewable Energy Policy of 2007, and the climate change policy of 2015 advocating for promoting clean energy technologies. The biofuels Act of 2018 provides a framework for regulating biofuel production, distribution, and use; nonetheless, this is yet to be operationalized. A Biofuels General Regulations was also drafted in 2020 to guide the initial blending of 5 percent for ethanol and biodiesel. While a fuel blend of up to 20 percent is envisaged in the Biomass Resource Management Investment Priorities for 2020/21 (MEMD, 2020), it has not been achieved.

3.0 The analytical general equilibrium model

Our analysis is rooted in general equilibrium theory and a competitive market structure. We adapt the GE model by Devadoss and Bayham (2010) and introduce multiple policy instruments. In our model, all policies are revenue-neutral. Therefore, we explicitly account for the tax interaction and revenue recycling effects (Bento & Jacobsen, 2007). We evaluate a feedstock production subsidy, an ethanol consumption subsidy, a combination of the two subsidies, and a gasoline tax[11]. The model comprises one representative household, the production sector, the government, and the trade sector.

The representative household derives utility from the blended fuel (FL), food (FD), and composite good (X). FL is a blend of ethanol (E) and gasoline (G), and contrary to Devadoss and Baymam, gasoline is only imported in our model [12]. Fuel generates pollution, creating a negative externality. Pollution is exogenous in the model, and it affects utility through a pollution function: $Z\big(FL(G,E)\big)$. The utility function is given in Equation (1):

$$U = u\left(FL, FD, X, -Z\big(FL(G,E)\big)\right) \quad (1)$$

We assume separability in the utility function (see Bento & Jacobsen, 2007; Taheripour et al. (2008) such that the emissions from the final fuel have no impact on the consumers' choice of *FL*, *FD*, and *X*.

Households earn income from land rent, the rental rate on capital, labor wages, and government transfers. They spend it on fuel, food, and the composite good. The household budget constraint is as specified in Equation (2):

$$r_R\bar{R} + r_K\bar{K} + w\bar{L} + GT = P_L^C F_L + P_D^C F_D + P_X^C X \quad (2)$$

[11] We do not include a producer subsidy since in principle its analysis is close to that of a consumption subsidy, particularly when the commodity is nontraded. In our analysis, ethanol is neither imported nor exported.
[12] Uganda imports all the gasoline.

where $\bar{R}$ is land, $\bar{K}$ capital (sector-specific in food production), $\bar{L}$ labor, r_R land rent, r_K capital rental rate, w the wage rate, GT government transfers (fixed in real terms), P_L^C the consumer price of fuel, and P_D^C the consumer price of food. The price of the composite good P_X is set as the model numeraire.

Food production uses land, capital, and labor. Without loss of generality, we ignore food imports in the analytical model, but this is relaxed in the computational analysis. Ethanol employs only labor and capital, while all the gasoline is imported. We assume constant returns to scale technologies and firms earn zero profits, so we arrive at the following in our respective markets:

The food market:

$$P_D^P = MC_D(r_R, r_K, w) - S_D \quad (3)$$

$$P_D^c = P_D^P \quad (4)$$

$$F_S = F_D + F_E + F_X \quad (5)$$

where P_D^P is the producer price for food/feedstocks, MC_D denotes the marginal cost, and S_D is the feedstock production subsidy. Food supply (F_S) is the sum of food demand (F_D), feedstock demand (F_E), and net food exports (F_X).

The ethanol market:

$$P_E^P = MC_E(P_D^C, r_K, w) \quad (6)$$

$$P_E^c = P_E^P + t_e - S_E \quad (7)$$

$$E_S = E_D \quad (8)$$

P_E^P is the ethanol producer price, MC_E the marginal cost, P_E^c the ethanol price to blenders, t_e the ethanol tax, and S_E the ethanol consumption subsidy. In equilibrium, total domestic demand (E_D) equals domestic supply (E_S) since ethanol is not traded.

The gasoline market:

$$P_G^P = P_G^W + tm \quad (9)$$

$$P_G^c = P_G^P + tg \quad (10)$$

$$G_M = G_D \quad (11)$$

P_G^P is the gasoline supply price, P_G^W the world price, tm the import tariff, tg the consumption tax, and the same tax is increased to finance the subsidies. In equilibrium, domestic demand (G_D) equals imports (G_M).

The fuel market:

$$P_F^P = MC_F(\, P_G^c, P_E^c) \tag{12}$$

$$P_F^P = P_F^c \tag{13}$$

$$F_{LS} = F_L \tag{14}$$

P_F^P is the producer price for the blended fuel and MC_F denotes the marginal cost. Note that this sector does not have value-added because we assume blending by fuel suppliers. Domestic supply (F_{LS}) equals domestic demand (F_L) and the fuel is not traded.

The composite good:

$$P_X^P = MC_X(\, r_R\, , r_{K,}w) \tag{15}$$

$$X_S = X + X_X \tag{16}$$

P_X^P is the producer price of the composite good, MC_X is marginal cost, and in equilibrium, total supply X_S equals domestic consumption (X) plus net exports (X_X).

Factor market equilibrium:

$$\bar{R} = R_F + R_X \tag{17}$$

$$\bar{K} = K_F + K_E + K_X \tag{18}$$

$$\bar{L} = L_F + L_E + L_X \tag{19}$$

The subscripts follow the commodity notations such that total factor supply equals total demand by the respective sectors.

The government budget equates revenues to expenditure:

$$t_m G_M + t_g G_D + t_e E = S_D F_S + S_E E + GT \tag{20}$$

The trade balance equates the value of exports to that of imports.

$$P_D^c F_X + X_X = P_G^W G_M \tag{21}$$

Analytical results

This section presents only the final expressions. Full derivations are found in Appendix A.1. A positive term indicates a welfare improvement, and the reverse is true for a negative. The subsidies are budget-neutral, financed by a tax on gasoline t_g, while a reduction in the ethanol tax t_e counterbalances the gasoline tax instrument. We explicitly assess the policy impacts on pollution, tariff revenues, the trade balance, and taxpayer costs. We can also infer the effect on factor employment, and income. The ultimate change in welfare, measured by utility, is an empirical question examined in our computable model. Note that the amount of ethanol is assumed to be mandated, whereby substitution between the two fuels beyond the mandated ethanol volume is irrelevant. Furthermore, for the convenience of exposition, we do not include the expression for the change in the rental rate of sector-specific capital with respect to the changes in the policies. Therefore, this assumption is directly implemented in the numerical model.

Impact of a feedstock subsidy

$$\frac{1}{\lambda}\frac{dU}{dS_D} = -\overbrace{\overbrace{\left[\frac{u_Z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D} - \overbrace{t_g\frac{\partial G_D}{\partial P_F}\frac{dP_F}{dS_D}}^{Interaction\ effect} - \overbrace{t_g\frac{\partial G_D}{\partial t_g}\frac{dt_g}{dS_D}}^{Revenue\ recycling\ effect}\right]}^{Gasoline} - \overbrace{\left[\frac{u_Z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D} - t_e\right]\frac{dE_D}{dS_D}}^{Ethanol\ effect}}^{Pigouvian\ effect} - \overbrace{S_D\frac{dFS}{dS_D}}^{Subsidy\ effect} + \overbrace{t_m\frac{dG_M}{dS_D}}^{Tariff\ effect}$$

$$\overbrace{\overbrace{-P_G^W\frac{dG_M}{dS_D} - (1-e_o)G_M\frac{dP_G^W}{dS_D}}^{Gasoline} - \overbrace{P_D^W\frac{dF_X}{dS_D} + \left(1-e_f\right)F_X\frac{dP_D^W}{dS_D}}^{Food}}^{Trade\ effect} \qquad (22)$$

The Pigouvian effect

Both the tax and subsidies stimulate ethanol production and displace gasoline. For example, in Equation 22, a feedstock subsidy lowers the cost of feedstocks, boosting ethanol production. This causes a chain of effects. First, in all the derived expressions, λ refers to the marginal utility of income. The Pigouvian effect consists of the gasoline and ethanol effects. The gasoline subcomponent comprises the damages from gasoline pollution per unit of money and a corresponding tax that would offset it. Note that the tax expressions here comprise the interaction and revenue recycling effects because the financing tax is imposed on gasoline. We will be discussing these later.

The ethanol subcomponent depicts the difference between the marginal social costs represented by the first term and the tax on the share of ethanol in the final fuel. In principle, the first term would be the marginal benefit to society if ethanol emissions are lower compared to gasoline. The welfare impact of ethanol will therefore depend on the pollution outcome. This implies that it is possible to have a counterproductive subsidy if pollution levels rise, causing marginal social damages to exceed the tax. However, assuming ethanol emits less GHGs than gasoline, the overall Pigouvian effect of the two fuels could be welfare improving, neutral, or detrimental depending on the change in gasoline consumption relative to the change in ethanol. That is, when: the change in gasoline consumption (ΔGD) < the change in ethanol (ΔED), there is no rebound effect, and total fuel consumption declines; $\Delta GD = \Delta ED$, the impact could be neutral; $\Delta GD > \Delta ED$, there is a rebound effect in fuel consumption, and the policy tool is counterproductive.

Note, however, that sector-specific capital in agriculture may influence the outcome. Bento and Jacobsen (2006) demonstrated how a fixed input might weaken the effect of the environmental tax on the price of the polluting good, limiting the targeted reduction in output. Therefore, we examine this assumption in the numerical model in relation to a subsidy.

Subsidy interaction and revenue recycling effects

The financing tax for the subsidies is imposed on gasoline; hence, the subsidy interaction and revenue recycling effects are associated with gasoline [13]. The interaction effect in Equations 22, 23, and 24 (page 12) shows how a feedstock subsidy (ethanol subsidy) reduces the price of feedstocks (ethanol), causing a decline in their cost. This increases household purchasing power and boosts the consumption of commodities, including gasoline. This term is welfare-improving with regard to other commodities, except gasoline. In contrast, the revenue recycling effect unequivocally reduces welfare due to the increased tax on gasoline to finance the subsidy.

The subsidy effect

The feedstock and ethanol subsidies increase government expenditure and thus the marginal social cost in Equations 22, 23, and 24. This component impacts welfare negatively and should be more significant under the feedstock subsidy because it is assumed that every unit of the output is subsidized regardless of its destination market.

[13] We remind the reader that the interaction effect in a general equilibrium model goes beyond a particular good but is associated with any commodity that has cross-price elasticity with the taxed good (Williams, 2000).

The tariff effect

All policies induce ethanol production and offset the demand for gasoline. This results in a corresponding decline in gasoline imports and import tax revenues (Devadoss and Beyham, 2010; Taheripour & Tyner, 2014). Therefore, the tariff effect should be welfare-reducing because of the loss in revenue.

The trade effect

The substitution of ethanol for gasoline reduces gasoline imports, as reflected in Equations 22, 23,24, and 25. The trade effect comprises gasoline imports and food exports. The first term under gasoline shows a reduction in the volume imported. In the second term, world market prices are exogenous because of the small-country hypothesis. It, therefore, collapses to zero for all imports and exports. All policies reduce gasoline imports and save foreign exchange; hence, the overall trade effect for gasoline is welfare-enhancing. This also reveals the possibility of an improved trade balance.

Regarding food exports, ethanol production increases the demand for feedstock/food, and exports fall. The first term under the food component is welfare-increasing, as food exports are diverted to the domestic market. However, the final impact on welfare will depend on the distribution between consumption by households and ethanol processing.

The welfare impact of the ethanol consumption subsidy

$$\frac{1}{\lambda}\frac{dU}{dS_E} = -\overbrace{\overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_E} - t_g\overbrace{\frac{\partial G_D}{\partial P_E}\frac{dP_E}{dS_E}}^{Tax\ interaction\ effect} - t_g\overbrace{\frac{\partial G_D}{\partial t_g}\frac{dt_g}{dS_E}}^{Revenue\ recycling\ effect}\right]}^{Gasoline} - \overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D} + \overbrace{S_E}^{Ethanol\ Subsidy\ effect} - t_e\right]}^{Ethanol}\frac{dE_D}{dS_E}}^{Pigouvian\ effect} + \overbrace{t_m\frac{dG_M}{dS_E}}^{Tariff\ effect}$$

$$\overbrace{\overbrace{-P_G^W\frac{dG_M}{dS_E} - (1-e_o)G_M\frac{dP_G^W}{dS_E}}^{Gasoline} - \overbrace{P_D^W\frac{dF_X}{dS_E} + \left(1-e_f\right)F_X\frac{dP_D^W}{dS_E}}^{Food}}^{Trade\ effect} \qquad (23)$$

The welfare effect of a feedstock and ethanol subsidy

$$\frac{1}{\lambda}\frac{d^2U}{dS_D S_E} = -\overbrace{\left[\overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D}\right]\frac{dG_D}{dS_E} - \overbrace{t_g\left[\frac{\partial G_D}{\partial P_F}\frac{dP_F}{dS_D}\right]\frac{dP_E}{dS_E}}^{Subsidy\ interaction\ effect} - \overbrace{t_g\left[\frac{\partial G_D}{\partial t_g}\frac{dt_g}{dS_D}\right]\frac{dt_g}{dS_E}}^{Revenue\ recycling\ effect}}^{Gasoline}\right] - \overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D} - t_e\right]\frac{dE_D}{dS_D}\frac{dE_D}{dS_E}}^{Ethanol\ effect}}^{Pigouvian\ effect} -$$

$$\overbrace{S_D\frac{dFS}{dS_D}\frac{dFS}{dS_E}}^{Subsidy\ effect} + \overbrace{t_m\frac{dG_M}{dS_D}\frac{dG_M}{dS_E}}^{Tariff\ effect} \overbrace{\overbrace{-P_G^W\frac{dG_M}{dS_D}\frac{dG_M}{dS_E} - (1-e_o)G_M\frac{dP_G^W}{dS_D}\frac{dP_G^W}{dS_E}}^{Gasoline} - \overbrace{P_D^W\frac{dF_X}{dS_D}\frac{dF_X}{dS_E} + \left(1-e_f\right)F_X\frac{dP_D^W}{dS_D}\frac{dP_D^W}{dS_E}}^{Food}}^{Trade\ effect} \quad (24)$$

Equation 24 combines the effects of a feedstock subsidy (Equation 22) and an ethanol subsidy (Equation 23); the ethanol subsidy moderates every component.

The welfare impact of a consumption tax on gasoline

$$\frac{1}{\lambda}\frac{dU}{dt_g} = -\overbrace{\overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D} - tg\right]\frac{dG_D}{dt_g}}^{Gasoline} - \overbrace{\left[\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dt_g} - \overbrace{t_e\frac{\partial E_D}{\partial P_g}\frac{dP_g}{dt_g}}^{Tax\ interaction\ effect} - \overbrace{t_e\frac{\partial E_D}{\partial t_e}\frac{dt_e}{dt_g}}^{Revenue\ recycling\ effect}\right]}^{Ethanol\ effect}}^{Pigouvian\ effect} + \overbrace{t_m\frac{dG_M}{dt_g}}^{Tariff\ effect}$$

$$\overbrace{\overbrace{-P_G^W\frac{dG_M}{dt_g} - (1-e_o)G_M\frac{dP_G^W}{dt_g}}^{Gasoline} - \overbrace{P_D^W\frac{dF_X}{dt_g} + \left(1-e_f\right)F_X\frac{dP_D^W}{dt_g}}^{Food}}^{Trade\ effect} \quad (25)$$

A gasoline tax boosts ethanol production by increasing the cost of gasoline relative to ethanol, and the tax on ethanol is reduced to maintain a balanced budget. This makes ethanol competitive, and blenders substitute it for gasoline. Note that substitution occurs only until the mandated volume is generated. As observed in Equation 25, the tax interaction and revenue-recycling effects are part of the ethanol subcomponent. The tax interaction effect reflects an increase in the cost of gasoline and a decline in household purchasing power. This affects the consumption of goods, including ethanol. On the other hand, the revenue recycling effect is an efficiency gain as gasoline tax revenue is used to finance the tax cut on ethanol. It lowers the cost of ethanol, further augmenting the direct policy-induced ethanol production.

Assuming ethanol emits less GHGs than gasoline, the overall welfare impact of all policies will depend on whether the sum of all the right-hand side terms is positive or negative. This is an empirical question assessed in our computable model.

4.0 The computable model and data

The computed model is a computable general equilibrium model (CGE), an applied version of the analytical model in section 3.0. We use the PEP-1-1 standard single-country static CGE model by Decaluwé et al. (2013), calibrated to the 2016/17 Uganda SAM version by Nakamya and Romstad (2020). The original SAM was developed by Tran, Roos, Asiimwe, and Kisakye (2019) and was obtained from the Ministry of Finance, Planning, and Economic Development. We also obtained data on imports and consumption volumes of petroleum and gasoline and gasoline price from the Ministry of Energy and Mineral Development and the Uganda Bureau of Statistics (UBOS). Ethanol prices are from ethanol processors. The elasticity parameters were obtained from the literature, and the technical coefficients for the ethanol types are from Zhou and Kojima (2011). All the above data are adopted as used in Nakamya and Romstad.

Only four industries were explicitly stated in the analytical model. The rest were grouped under the composite good, X. This assumption is relaxed in the empirical model by including all the sectors and commodities in the SAM (34 sectors and commodities). The production structures employ a Leontief production function at the top and to individual intermediate inputs, except for the Ethanol-collecting and Ethanol-blending sectors, which use a constant elasticity of substitution (CES) function [14]. The value-added also employs a CES function for the land-capital and labor composites, and these as well use the same function for their components. Domestic output is allocated between exports and domestic consumption using a constant elasticity of transformation (CET) function, while total domestic consumption is a CES function of domestic production and imports. World prices of imports and exports are exogenous because we assume a small country hypothesis.

The model contains 32 households categorized by the Central, Eastern, Northern, and Western regions. They obtain income from factor endowment plus transfers. They spend it on savings, taxes, and consumption, modeled as linear expenditure systems derived from the maximization of a Stone-Geary

[14] This functional specification implies perfect substitution between ethanol and gasoline, but only for the mandated volume. It is a convenient way to displace gasoline with ethanol. Besides, blend levels of up to 10% permit an equivalence of the units of gasoline and ethanol (Macedo et al., 2008). We therefore choose a very high elasticity of substitution parameter of 120.

utility function. Land is underutilized and mobile in agriculture [15], and we assume unemployment in the labor market. Capital is fixed in supply and fully employed. It is mobile across the non-agricultural sectors but sector-specific in agriculture [16]. The GDP deflator is the model numeraire, and the savings-investment balances are savings-driven, with endogenous investments. Government savings is a flexible residual between revenues and expenditures, and all tax (subsidy) rates are fixed.

The adapted model structure is found in Nakamya and Romstad (2020). Details on the adjustments, elasticity parameters, and the calculation of the mandated volume are also found in the same study under Appendix A. in the Supplementary data file [17]. However, see Decaluwé et al. (2013) for the complete PEP-1-1 standard model.

4.1 Policy implementation, scenario, and policy evaluation

Policy implementation

We simulate 70.3 million liters of ethanol, worth Ush.211.05 billion [18]. This volume is equivalent to a 10 percent blend level according to the 703 million liters of gasoline in the base year. Each ethanol type contributes an equal share to total production, and this allows further comparison across feedstocks. We chose the 10 percent blend level since the current vehicle fleet can run on it without complications. We also found this volume less ambitious for an infant ethanol industry. We counterbalance the subsidies with an increase in the gasoline tax and reduce the ethanol tax in the gasoline tax policy.

Main scenario

We run one scenario, hereafter the main scenario, based on the baseline model assumptions stated in section 4.0. We then simulate ethanol production under four policy cases: the feedstock subsidy, ethanol consumption subsidy, a combination of both subsidies, and a gasoline tax. We first determined the adequate ethanol consumption subsidy rate of about 0.33 per liter. From this, we derive the feedstock subsidy rates, as shown in the calculations of Appendix C. These rates are 0.121, 0.124, and 0.026 for

[15] Agriculture in this case refers to only the crop sectors. It excludes fishing, forestry and animal husbandry.
[16] This paper builds on our earlier study, Nakamya and Romstad (2020), hence we maintain the same assumptions.

[17] This can be downloaded from https://doi.org/10.1016/j.esd.2020.10.003
[18] This is equivalent to USD 70.4 million at the exchange rate of Ush.3000/ USD. We use the basic price of Ush. 3000[18] per liter to transform that volume to a nominal value of Ush. 211.05 billion.

maize, cassava, and sugarcane ethanol, respectively. We simulate an equal volume under each policy case instead of assuming a similar budget. Therefore, each policy determines its budget requirements.

Policy evaluation

In order to evaluate the policies, we selected a set of indicators with a bias toward best practices that enhance benefits rather than meeting minimum sustainability standards (Von Maltitz & Stafford, 2011). We compare the change in household welfare measured using equivalent variation (Taheripour et al., 2008). Equivalent variation (EV) is the amount of income that would have the same impact on a consumer's (household) welfare as the policy would. EV in Equation 26 is derived from linear expenditure systems. It is reported in absolute terms (in billions of Uganda shillings), and a positive value indicates welfare gains. We also used other indicators like real GDP. Despite its limitations, GDP can be used to at least proxy economic wellbeing (Dynan& Sheiner, 2018). In this regard, we include household income and consumption as these are well-known dimensions of economic welfare. We also report the gross budget allocation to determine the immediate cost. Nonetheless, we still acknowledge that welfare costs go well beyond the immediate budgetary costs of a subsidy (Schwartz & Clements,1999). Changes in imports and exports volume indices are considered since these influence the trade balance. Therefore, in line with the study objectives, the indicators in Table 5.1 were found appropriate.

$$EV = \prod_i \left(\frac{PCO}{PC}\right)^{\gamma i} * \left(CTH - \sum_i PC * CMIN\right) - \left(CTHO - \sum_i PCO * CMIN\right) \qquad (26)$$

EV is the equivalent variation. PCO and $CTHO$ refer to the old purchaser price and household consumption budget, while PC and CTH are post-regulation purchaser price and consumption budget, respectively. $CMIN$ is the minimum consumption level, and γi the marginal expenditure shares. The index i represents the commodities consumed by the household.

Sensitivity and scenario analysis

We conduct a sensitivity analysis to test the robustness of the results by choosing different elasticity parameters for land, capital, and labor. We focus on the factors of production since substitution between gasoline and ethanol is irrelevant for mandated consumption. We also do a scenario analysis to test the implication of specific agricultural capital for biofuel policy outcomes. Therefore, we run a parallel simulation when all the factors of production in agriculture are mobile and compare the results with those from the main scenario.

5.0 Results and discussion

Unless otherwise stated, we report all results as percentage deviations from the base year equilibrium values. Our results are suggestive and only shed light on the possible policy alternatives.

Main scenario

This section presents the findings from all the policy cases.

5.1. Summary of the policy evaluation

First, we present a summary of our policy evaluation in line with the analytical model. This is a simplistic assessment based on the indicators in Table 5.1. The results in the Table are only rankings.

Table 5.1 Summary of the evaluation

	Feedstock subsidy	Consumption Subsidy	Consumption tax on
Agricultural output	1	3	2
Value added	1	3	2
Real GDP	1	3	2
CPI	1	2	3
Household Income	1	3	2
Welfare	1	-	-
Budget	2	1	NA
Change in government income	2	3	1

The rating scale runs from 1 to 3, reflecting a best to the worst outcome. NA means "not applicable" because there is no subsidy budget but an increase in the tax rate on gasoline.

All policies are analyzed in a second-best setting with pre-existing taxes on gasoline and ethanol. The feedstock subsidy appears to be the most effective across most indicators but involves the highest taxpayer costs. Funding a huge budget would negatively impact welfare. Nonetheless, the growth in agricultural output, real GDP, and income seem to surpass the financing burden, causing a positive change in welfare of mostly the rural households. The ethanol consumption subsidy requires a slightly smaller budget than the feedstock subsidy; however, it puts upward pressure on feedstock/food prices. On the other hand, the gasoline tax performs relatively better than the consumption subsidy in most indicators because the tax is counterbalanced with a reduction in the ethanol tax, which acts as a tax credit. However, the gasoline tax policy increases all commodity prices, resulting in the biggest change in the CPI and a significant reduction in household welfare.

In line with the analytical model, all policies have a negative tariff effect. By restricting ourselves to only the pump-to-wheel ethanol emissions, all cases generate a positive impact from the Pigouvian component. The reduction in imports exceeds the decrease in exports; nonetheless, the trade balance can only be sustained if exports are maintained. The effect on utility measured by the change in equivalent variation in Figure 5.2 shows welfare gains for only the feedstock subsidy. We continue to provide a detailed discussion of the results in the following section.

5.2 Detailed presentation and discussion of the results

This section provides the detailed findings and discussion for each policy.

The ethanol consumption subsidy

In all policy cases, the mandated volume of ethanol determines the amount of feedstocks. Typically, the price of feedstocks rises due to the derived demand from the ethanol industry induced by the consumption subsidy. In order to control for the subsidy financing effect in our interpretations, we first ran simulations where the government budget was unbalanced [19]. In line with theory, we find that a consumption subsidy raises the producer price of ethanol and thus the unit price before transaction costs and taxes (subsidies) while lowering the purchaser to blenders. However, the budget is balanced for all the results in this paper; therefore, the counter-financing tax causes the purchaser price of ethanol to rise [20].

From conventional wisdom, the purchaser price of gasoline is expected to fall because gasoline is displaced. It instead rises because of the tax we imposed on gasoline to finance the subsidy. The increase in gasoline and ethanol prices translates into a higher price for the final fuel and causes its consumption to decline. In Table 5.2, we report the changes in prices and consumption. With reference to the analytical model, we can argue that the Pigouvian component in the welfare function is welfare-improving if only pump-to-wheel ethanol emissions are considered. Our results underscore the argument that a rebound effect is unlikely if a subsidy is counter-financed by a tax. They align with the view and findings by Taheripour and Tyner (2014). Taheripour and Tyner argue that fuel consumption may not necessarily be subsidized. They reported no rebound effect in all the scenarios about US ethanol. Their ethanol subsidy was counter-financed by a tax on gasoline, a reduction in an agricultural subsidy, or a corresponding increase in the income tax. Moreover, there are several feedback effects in a GE model, for example, the

[19] We run this simulation for comparison purposes but the results are not reported.
[20] The uniform change in the ethanol prices follows from the assumed uniform baseline price for all ethanol types[20].

contraction of some activities due to resource reallocation. Such effects may reduce the demand for inputs, including fuel, as revealed in our findings [21].

Given the growth in total value-added, agricultural output, real GDP (See Table 5.3), and household income (Figure 5.1), we attribute a decline in welfare (Figure 5.2) to the subsidy financing burden. This is also proved to hold in the unbalanced budget case.

The feedstock production subsidy

The feedstock subsidy affects the market price of ethanol indirectly. It raises the producer price of feedstocks but reduces the market price. Owing to the significant share of the feedstock cost in the total ethanol production costs, a fall in the price of feedstocks significantly reduces the marginal cost of ethanol and its unit price before tax. The subsidy is directed to farmers, generating the highest increase in agricultural output of about 1.15 percent. As a result, the production of feedstocks increases significantly, boosting their exports and causing a corresponding decline in imports. Therefore, in terms of the trade effect of food exports in the analytical model, the feedstock subsidy reduces welfare while imports enhance it.

Contrary to the ethanol consumption subsidy, the feedstock subsidy takes a large budget for the same volume of ethanol because every unit of output is subsidized irrespective of the destination market (see Table 5.3). Therefore, it results in high taxpayer costs and a significant rise in gasoline, ethanol, and blended fuel prices. Nonetheless, this policy generates substantial growth in most variables and the smallest increase in the CPI (see Table 5.3). For example, household income and welfare increase the most, particularly for rural households (Figures 5.1 and 5.2). Gardener (2007) demonstrated in a partial equilibrium framework how an agricultural subsidy generates more gains for the farmers than an ethanol subsidy in the short run.

Similar to the consumption subsidy, there is no rebound effect because fuel consumption declines (Table 5.2). Therefore, the welfare impact of the Pigouvian component of the analytical model is positive.

A tax on gasoline

The impact of a gasoline tax is analogous to the case of a mandate in raising the cost of gasoline. The tax raises the price of gasoline above that of ethanol, making ethanol competitive. In order to balance the budget, the tax on ethanol is reduced, weakening the negative interaction effect on ethanol. This further enhances ethanol production and consumption. However, since gasoline constitutes the largest share of

[21] Because of the limited space, these findings are not reported here.

the final fuel, an increase in its price drives up the price for the final fuel and a fall in demand. This directly affects economic activities through an increased cost of fuel. In addition to the higher fuel prices, the competition for resources by the feedstock and ethanol sectors exacerbates the rising costs. Overall, production costs in the economy rise. As a result, the prices of feedstocks, ethanol, and other commodities rise significantly, and the increase in the CPI of 026 percent is the highest among all policy cases. Nonetheless, agricultural output, total value-added, and real GDP increase. This is partly because the reduction in the ethanol tax acts as a tax credit, hence, attenuating the increase in costs. Although this case registers a modest growth in most variables, the highest increase in prices causes substantial welfare losses for all households (see Figure 5.2).

Contrary to our study, Ge and Lei (2017) report a decline in the gasoline price from implementing a gasoline tax to promote bioethanol in China, and their CPI falls too. They attribute this outcome to the reduced demand for gasoline due to the high price, which leads to a decline in domestic gasoline production and a fall in factor employment in the gasoline sector. This triggers second-round effects of lower gasoline prices, lower production costs in other sectors, and a general fall in the CPI. This suggests more potent indirect effects than the direct impacts of the tax. Besides, their analysis involves domestically produced gasoline, while all the gasoline in the current study is imported.

5.3 A two-part policy

It is essential to achieve the benefits of ethanol amid reasonable budget resources while avoiding the counterintuitive consequences of increasing emissions and soaring food prices. However, our findings tend to reveal some extreme outcomes. For instance, the feedstock subsidy ranks the best across most indicators, and a sustainable feedstock supply is crucial. Yet, the highest taxpayer costs constitute a significant limitation to financially-constrained economies. Although it generates the highest household income growth and welfare improvement, this mainly occurs for rural households.

On the other hand, the gasoline tax and the ethanol consumption subsidy drive up food prices. Their performance is moderate; however, unlike the feedstock subsidy that targets farmers, they induce reasonable income distribution across all household types (see Figure 5.1). The consumption subsidy, in particular, has an added advantage of a smaller resource budget because of a small targeted ethanol sector. Therefore, we suggest a combination of a feedstock and consumption subsidy. In our simulation, we keep adjusting the share of each subsidy amount in the total funding requirements for the two-part policy. We then examine the results of key economic variables to determine the suitable combination (see Table 5.4).

Results (combination of a feedstock and an ethanol consumption subsidy)

de Gorter and Just (2009b) demonstrated how an ethanol tax credit reduces the tax costs of the loan rate to farmers (a farm subsidy) while the loan rate raises the tax costs of the tax credit (ethanol subsidy). The net impact on the total tax costs is ambiguous *apriori*. In our analysis, a combination of a feedstock and ethanol subsidy produces results that lie between the extreme findings from each policy, and our total taxpayer costs show a net reduction. Table 5.3 shows the individual budgets for the feedstock and ethanol consumption subsidies: 415 and Ush.88 billion shillings, respectively. However, based on the values in Table 5.4, a combination of 150 and Ush.58 billion budgets corresponding to the feedstock and ethanol subsidies, respectively, emerges as the best. This yields a total budget of only Ush.208 billion. Hence, the tax costs for both policies are reduced, yet key variables indicate good performance.

The feedstock subsidy moderates the ethanol subsidy's effect on feedstock prices, yielding a modest rise. The prices of maize and cassava feedstocks, which also constitute a considerable portion of most households' consumption basket, decline. The change in the CPI of 0.08 percent is below the average of all CPI changes (see Table 5.4). Unlike the feedstock subsidy alone, the two-part instrument generates income (Figure 5.3) and welfare (Figure 5.4) across all household types.

Despite government efforts, agricultural performance has remained poor in most developing countries, such as Sub-Saharan Africa (Bjornlund et al., 2020). For example, the government of Uganda commits considerable resources toward inputs and other farmer support, yet agriculture's contribution to GDP is the least. Several factors have been put forward to explain the poor performance of agriculture, including market failures such as demand constraints (Diao & Dorosh, 2007). We, therefore, envisage that an ethanol subsidy may synergize with the existing support for agriculture to expand the crop market and enhance growth. In other words, the feedstock subsidy (agricultural support) boosts crop production while the ethanol subsidy induces demand.

We conclude the discussion of our results by noting that the trade effect would enhance welfare for all policies, except the feedstock subsidy, which increases food exports. This is because output diversion to domestic use is assumed to increase utility. Nonetheless, the distribution of this output between consumption and ethanol production also matters. We observe that food consumption only rises under the feedstock subsidy. Hence, the significant reduction in food prices reverses the negative impact of increased exports. Nonetheless, while import reductions surpass the decrease in exports, the trade balance can only improve if exports are sustained at positive levels.

The tariff effect is welfare-reducing for all policies because of a reduction in imports. Gasoline imports, in particular, decline significantly. The decrease in tariff revenue is of great concern to Uganda and similar developing countries because of the narrow tax bases. Nevertheless, government income remains positive in all cases.

All subsidies impose a cost on taxpayers through a counter-financing tax. The gasoline tax also places an economic burden on society. Together with the interaction and revenue recycling effects, these effects are compounded in the final impact on household welfare, which improves only under the feedstock subsidy and two-part policy. Considering only the pump-to-wheel ethanol emissions would imply a positive welfare impact from the Pigouvian component due to a fall in demand for the final fuel. Besides, transport-related externalities such as vehicular emissions, congestion, and road-related accidents would also be reduced.

Table 5.2 Percentage changes in output, trade variables, prices, and consumption for the main scenario

		Output	Exports	Imports	Producer price	Purchaser price	Consumption
Consumption subsidy	Maize	1.73	-1.45	11.59	1.38	1.55	-0.72
	Cassava	1.37	-1.82	8.98	1.40	1.29	-0.59
	Sugarcane	14.07	0.00	58.18	6.60	5.50	-2.94
	Gasoline			-16.73		4.44	-
	Blend	-0.39				4.29	-1.90
	Maize ethanol				1.10	1.25	
	Cassava ethanol				0.66	1.25	
	Sugarcane ethanol				4.13	1.25	
Feedstock subsidy	Maize	5.91	14.45	-16.40	4.69	-4.30	2.36
	Cassava	4.65	19.19	-22.43	4.03	-5.85	3.23
	Sugarcane	16.18	28.24	-9.11	7.20	-4.92	2.61
	Gasoline			-17.91		22.41	
	Blend	-1.64				22.23	-8.45
	Maize ethanol				-3.09	18.65	
	Cassava ethanol				-3.09	18.65	
	Sugarcane ethanol				-3.09	18.65	
Tax on gasoline	Maize	1.97	-1.23	11.89	1.55	1.71	-0.83
	Cassava	1.84	-2.00	11.12	1.89	1.73	-0.84
	Sugarcane	7.87	0.80	27.64	3.42	3.40	-1.59
	Gasoline					11.78	
	Blend	-0.88				11.60	-4.86
	Maize ethanol				1.24	8.38	
	Cassava ethanol				0.93	8.20	
	Sugarcane ethanol				2.17	8.83	

Note: * denotes imports since gasoline is not locally produced.
The large percentage deviation in the values of particularly sugarcane is due to the smaller baseline values.

Table 5.3 Percentage change in key parameters for the main scenario

	Feedstock subsidy	Consumption Subsidy	Tax on Gasoline
Import volume index	-1.06	-0.94	-1.01
Export volume index	-0.74	-0.70	-0.74
Agric. Output	1.15	0.45	0.47
Real GDP	0.51	0.05	0.08
Total value-added	0.15	0.07	0.08
CPI	0.04	0.10	0.26
Government income	0.78	0.69	2.16
Import tax revenue	-0.42	-0.37	-0.15
Subsidy	415*	88*	**

Note: *Refers to absolute values of the subsidy budget in billions of Uganda shillings. **Not applicable.

Table 5.4 Budget and percentage changes in key variables for a two-part policy assessment

Feedstock subsidy budget	Ethanol subsidy budget	Total Budget	Agric output	Real GDP	value-added	CPI	Demand for Fuel	Price of Maize	Price of Cassava	Price of Sugarcane	Price of Ethanol
415.00	0.00	415.00	1.31	0.57	0.16	0.04	-8.45	-4.30	-5.85	-4.92	18.65
299.00	28.00	327.00	1.08	0.43	0.14	0.06	-6.84	-2.67	-4.45	0.69	13.87
244.00	43.00	267.00	0.92	0.34	0.12	0.07	-5.70	-1.66	-3.07	1.85	10.69
150.00	58.00	208.00	0.76	0.24	0.11	0.08	-4.50	-0.62	-1.66	3.04	7.52
75	73.00	148.00	0.60	0.15	0.09	0.09	-3.23	0.45	-0.21	4.25	4.38
0.00	88.00	88.00	0.44	0.05	0.07	0.10	-1.89	1.55	1.29	5.50	1.25

The values of the budget are in billions of Uganda shillings.

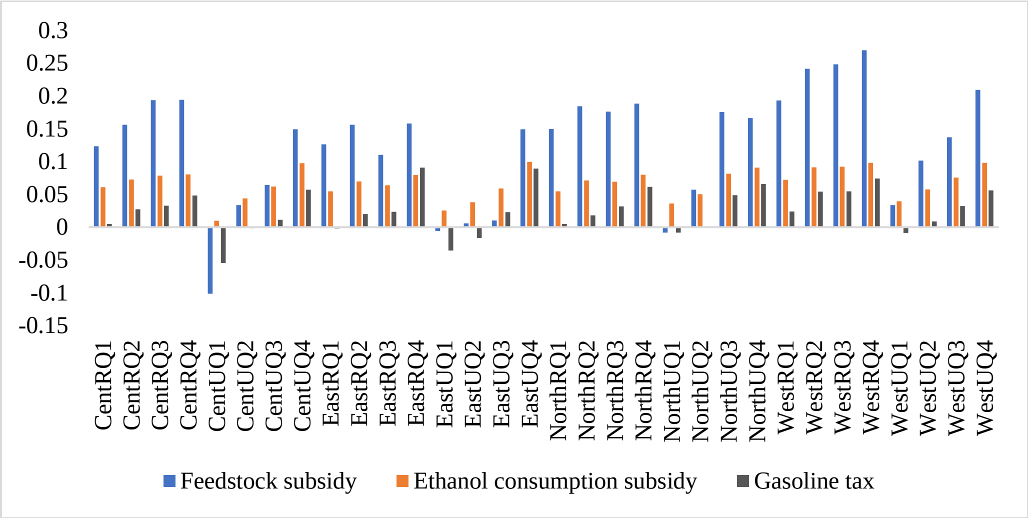

Figure 5.1 Percentage change in household disposable income for the main scenario

Note: The horizontal axis plots households for the central, eastern, northern, and western regions, with R for rural and U for urban. The Qs from 1 to 4 represent the four income quartiles. The same description applies to all the figures with households.

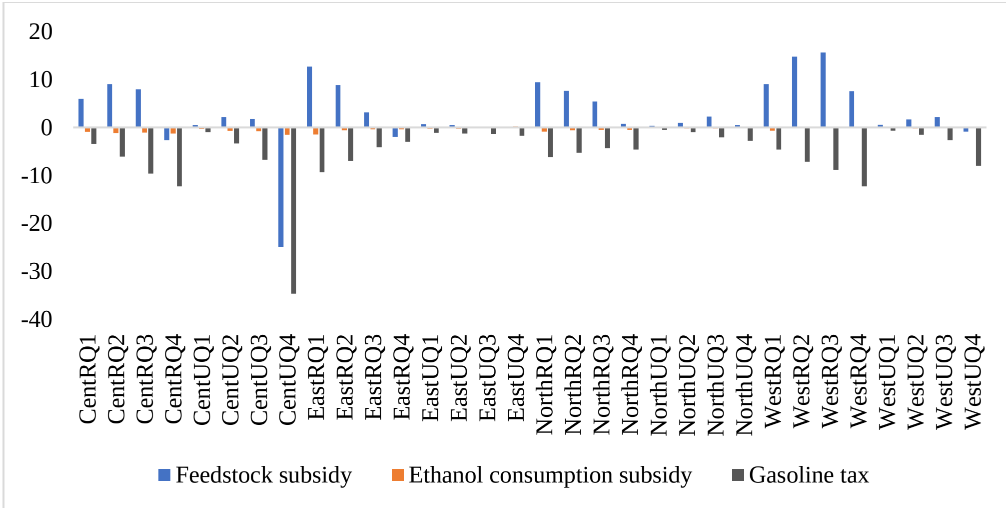

Figure 5.2 Change in Equivalent Variation (EV) for the main scenario
Note: EV is presented in absolute values measured in billions of Uganda shillings.

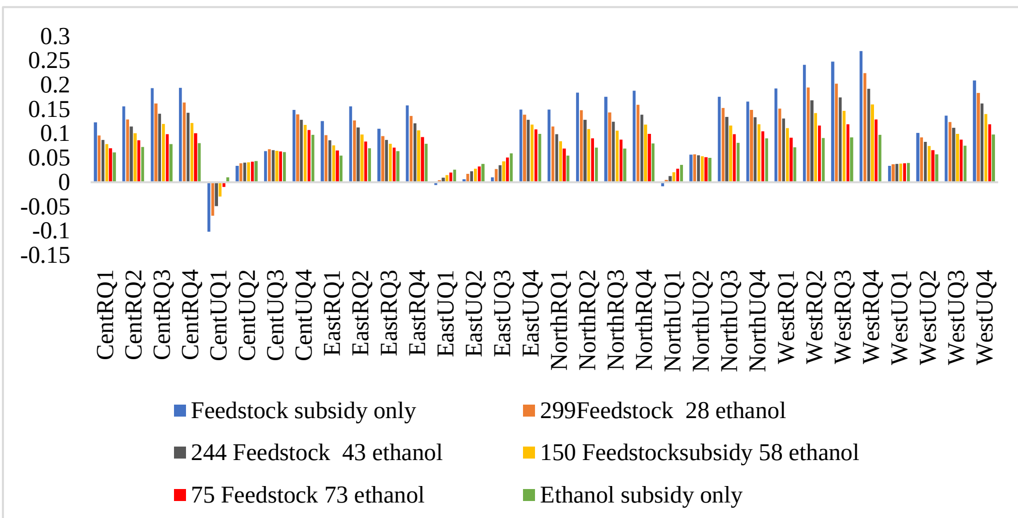

Figure 5.3 Percentage change in household disposable income for the two-part instrument assessment. Note feedstock and ethanol correspond to the feedstock and ethanol subsidies, respectively. The values correspond to the budget for each in billions of Uganda shilling.

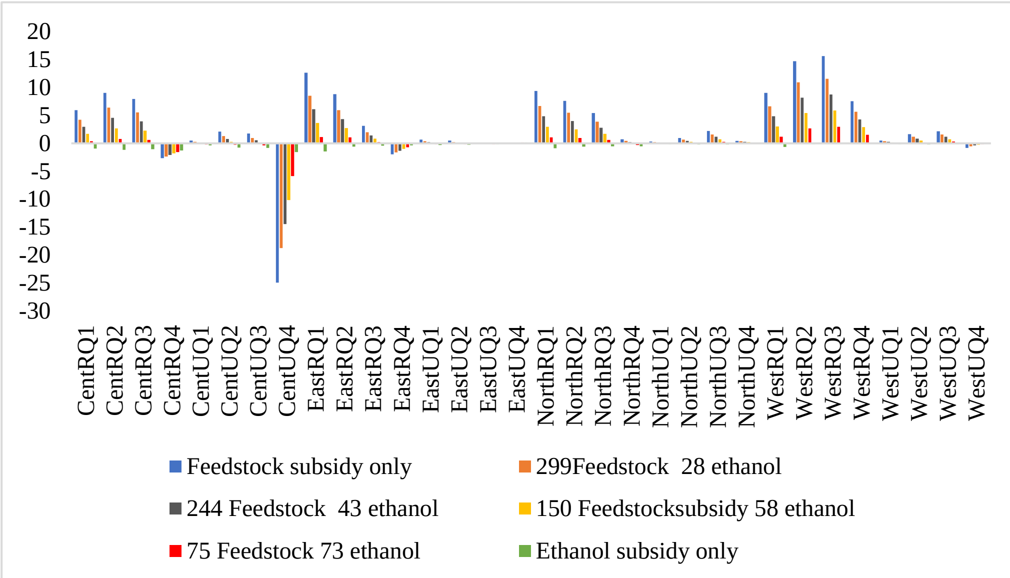

Figure 5.4 Change in Equivalent Variation (EV) for the two-part instrument assessment

5.5 Sensitivity and scenario analysis (SSA)

We test the robustness of our findings by varying the elasticity of substitution parameters for land, capital, and labor. We do this at the aggregate level between the capital and labor composites as well as at the lower level between the individual capital types (land and physical capital) and labor categories. The more elastic the substitution between land and capital, the stronger the growth in the variables for all policies. Hence, the relative performance of policies does not change. However, due to space limitations, Table 5.5 reports only results from the two-part policy since, according to our findings, it is suggested as the most efficient. In row B of Table 5.5, a higher elasticity of 0.6 between land and capital reduces feedstock prices, the CPI, and the subsidy budget relative to the two-part under the main scenario (row A). However, variations in the elasticity between labor and capital aggregates (rows D & E) and for individual labor types (row C) only cause marginal changes. We attribute this to the assumed unemployment in the labor market. As a result, the marginal product of labor remains lower relative to that of specific capital, causing only a smaller output response.

In the scenario analysis, we test the implication of capital specificity. Recall that our main scenario assumes sector-specific capital in agriculture (row A of Table 5.5). We still focus on the two-part policy and run a parallel simulation when all the primary factors are mobile. We then compare with the main scenario results. Bento and Jacobsen (2006) and Fraser and Waschik (2013) argued and showed that disregarding the existence of a fixed factor in the production of a polluting good may lead to overestimating the Pigouvian and the interaction tax effects of the environmental tax on that good. This occurs since the fixed factor captures part of the tax burden such that the price of the taxed good less than adjusts to the total change in the tax. Therefore, the reduction in the taxed good and the impact on real labor and total income are smaller. Even when possible labor supply increases are disregarded [22], the effectiveness of the tax is impaired. In this regard, a higher tax rate may be required to achieve the same level of the environmental target.

Our findings are in line with this argument. The presence of specific capital in agriculture attenuates the impact of the subsidy on feedstock prices, as observed in the main scenario (row A). Prices fall by less than when all the primary inputs are mobile (row F). It, therefore, takes a larger subsidy budget to produce an adequate volume of ethanol. On the other hand, the price of gasoline, which is assumed to bear the interaction effect, rises significantly. This effect and the increased taxpayer costs raise the final fuel price.

According to Bento and Jacobsen (2006), there are welfare gains from a revenue-neutral environmental tax in the presence of a fixed factor. First, the negative tax interaction effect is weakened due to a partial pass-through of the tax to the price of the taxed good. Second, labor supply may increase to compensate for the reduction in the Ricardian rent and real total income. In contrast, welfare changes from a subsidy should move in the opposite direction. Indeed our study shows lower welfare gains from a subsidy under capital specificity. Higher welfare gains are instead associated with factor mobility (Figure 5.5). Consistent with the interpretation in the two studies above, the fixed factor captures part of the subsidy. Therefore, a higher subsidy rate is required, which raises the taxpayers' burden. This results in a strong negative revenue recycling effect that weakens the positive interaction effect of the subsidy. We note that the difference in welfare changes under mobile and specific capital is relatively smaller. This is because only capital is specific while land (only cropland) is mobile across all crop sectors. Moreover, capital is just about 25 percent of the total capital stock in agriculture. Fraser and Waschik (2013) showed how welfare gains increase with the share of the specific factor. Therefore, in the case of a subsidy, welfare gains should decline with the share of the specific factor.

[22] According to Bento and Jacobsen (2007), labor supply may increase to compensate for the reduction in the fixed factor income due to a tax. They also assumed that the tax on the polluting good is counterbalanced by a reduction in the labor tax.

Table 5.5 Budget and percentage changes in key variables for a two-part policy assessment (SSA)

	Substitution parameters	Feedstock subsidy budget	Ethanol subsidy budget	Total subsidy budget	Real GDP	CPI	Gasoline price	Blend price	Ethanol price	Maize price	Cassava price	Sugarcane price	Blend demand
A	**(0.3 0.6 1.2)**	**150**	**58**	**208**	**0.24**	**0.08**	**10.92**	**10.75**	**7.52**	**-0.62**	**-1.66**	**3.04**	**-4.50**
B	(0.6 0.6 1.2)	140	58	198	0.27	0.07	10.39	10.22	7.01	-1.38	-2.71	2.17	-4.28
C	(0.3 0.9 1.2)	150	58	208	0.24	0.08	10.92	10.75	7.52	-0.62	-1.66	3.03	-4.50
D	(0.3 0.6 1.5)	149	58	207	0.24	0.08	10.88	10.72	7.49	-0.67	-1.73	2.98	-4.48
E	(0.3 0.6 0.9)	150	58	208	0.24	0.08	10.96	10.8	7.56	-0.56	-1.58	3.10	-5.70
	Scenario analysis												
F	(0.3 0.6 1.2)	124	58	182	0.21	0.05	9.62	9.45	6.26	-2.48	-4.23	1.02	-4.02

The row in bold represents scenario one findings (two part policy). The elasticity of substitution parameters in parenthesis are presented in the order of substitution between capital and land, labor categories, and aggregate capital versus aggregate labor. Row A relates to our main scenario, and F is the scenario simulation with fully mobile factors in agriculture. The rest of the rows, B, C, D, and E, also assume capital specificity in agriculture but differ from the main scenario based on their elasticity parameters. The values of the budget are in billions of Uganda shilling.

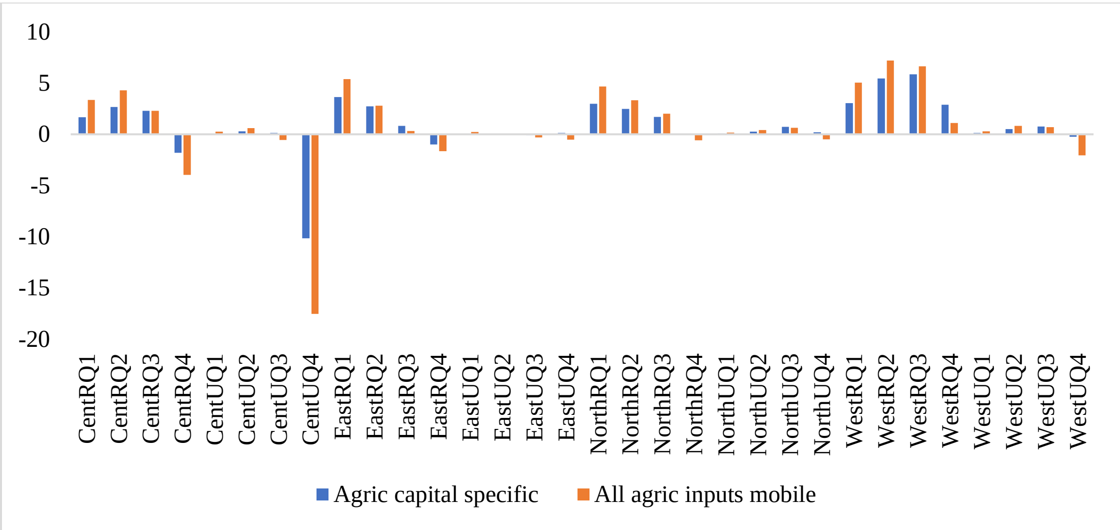

Figure 5.5 Change in Equivalent Variation (EV) from the scenario analysis

6.0 Conclusion and policy implications

This study uses a static CGE to evaluate the possible policy instruments to incentivize ethanol production in low-income countries. We assess the feedstock subsidy, an ethanol consumption subsidy, a combination of the two subsidies, and a gasoline tax. We apply the size of the subsidy budget and the effect on agricultural output, prices, total value-added, real GDP, government income, the trade balance, household income, and the overall welfare as performance indicators.

The feedstock subsidy generates substantial positive effects across all indicators but requires a large budget. The ethanol consumption subsidy takes the smallest budget and also performs reasonably well.

However, it causes a significant increase in food prices. Despite the high government income from the gasoline tax, it also increases prices and erodes household welfare. We, however, find a combination of a feedstock and ethanol subsidy as the most suitable policy.

Our computable model shows that the trade effect of the analytical model would enhance welfare for all policies, except for the feedstock subsidy, which increases food exports. Nonetheless, food consumption only rises under the feedstock subsidy, hence reversing the negative impact of increased exports. However, while import reductions surpass the decrease in exports, the trade balance would only improve if exports were sustained at positive levels.

Furthermore, the tariff effect of all policies is welfare-reducing because of a reduction in import revenue. Nevertheless, government income remains positive in all cases. All subsidies impose a cost on taxpayers through a counter-financing tax. The gasoline tax also places an economic burden on society. Considering only the pump-to-wheel ethanol emissions, the reduction in fuel demand implies a positive welfare impact from the Pigouvian component. Besides, transport-related externalities such as vehicular emissions, congestion, and road-related accidents would also be reduced. Household welfare improves only under the feedstock and two-part policy. Finally, the presence of sector-specific capital in agriculture impairs the effect of the feedstock and ethanol subsidy, raising the taxpayers' financing burden.

While the analytical model internalizes the pollution externality, the numerical model does not explicitly estimate pollution levels. Modeling pollution, especially in a dynamic framework, would reflect the trend in variables and provide additional insights. Besides, our policy assessment does not determine optimal subsidy or tax rates. Therefore, extending the model to calculate subsidy rates that maximize welfare would deliver interesting knowledge for policymakers.

CRediT authorship statement

Miria Nakamya: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. Eirik Romstad: Conceptualization, Validation, Resources, Writing - review & editing, Visualization, Supervision, Project administration.

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Conflicts of interest:

We declare no conflict of interest.

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Appendix A

We present the full derivation of the welfare effects of the feedstock subsidy, and this is extended to the ethanol production and consumption subsidies and the consumption tax on gasoline. The model is based on Devadoss and Bayham (2010, 2013).

$$L = u\left(FL, FD, X, -Z\big(FL(G,E)\big)\right) + \lambda(r_R\bar{R} + r_K\bar{K} + w\bar{L} + GT - P_L^C F_L - P_D^C F_D - P_X^C X) \qquad \text{A.1}$$

$$\frac{dL}{dF_L} = \frac{dU}{dF_L} - \lambda P_L^C = 0 \qquad \text{A.2}$$

$$\frac{dL}{dF_D} = \frac{dU}{dF_D} - \lambda P_D^C = 0 \qquad \text{A.3}$$

$$\frac{dL}{dX} = \frac{dU}{dX} - \lambda = 0 \text{ , considering the numeraire } P_X^C = 1 \qquad \text{A.4}$$

$$\frac{dL}{d\lambda} = r_R\bar{R} + r_K\bar{K} + w\bar{L} + GT - P_L^C F_L - P_D^C F_D - P_X^C X = 0 \qquad \text{A.5}$$

From the first-order conditions we derive the demand functions of F_D, F_L, X . we substitute them into the utility function to obtain the indirect utility function:

$$V = v(r_R, r_K, w, GT, P_L^C, P_{D,}^C - Z) \qquad \text{A.6}$$

Applying the envelope theorem on the indirect utility function, we arrive at the following expression.

$$\frac{dU}{dS_D} = \frac{\partial U}{\partial F_L}\frac{\partial F_L}{\partial P_L^C}\frac{\partial P_L^C}{\partial S_D} + \frac{\partial U}{\partial F_D}\frac{\partial F_D}{\partial P_D^C}\frac{\partial P_D^C}{\partial S_D} - \frac{u_z}{\lambda}\frac{dZ}{dS_D}$$

$$+\lambda\left(\bar{R}\frac{dr_R}{dS_D} + \bar{K}\frac{dr_K}{dS_D} + \bar{L}\frac{dw}{dS_D} + \frac{dGT}{dS_D} - F_L\frac{\partial P_L^C}{\partial S_D} - P_L^C\frac{\partial F_L}{\partial P_L^C}\frac{\partial P_L^C}{\partial S_D} - P_D\frac{\partial F_D}{\partial P_D}\frac{\partial P_D^C}{\partial S_D} - F_D\frac{\partial P_D^C}{\partial S_D}\right) \qquad \text{A.7}$$

$$\frac{dU}{dS_D} = \frac{\partial F_L}{\partial P_L^C}\frac{\partial P_L^C}{\partial S_D}\left(\frac{\partial U}{\partial F_L} - \lambda P_L^C\right) + \frac{\partial F_D}{\partial P_D^C}\frac{\partial P_D^C}{\partial S_D}\left(\frac{\partial U}{\partial F_D} - \lambda P_D^C\right) - F_L\frac{\partial P_L^C}{\partial S_D} - F_D\frac{\partial P_D^C}{\partial S_D} - \frac{u_z}{\lambda}\frac{dZ}{dS_D}$$

$$+\lambda\left(\bar{R}\frac{dr_R}{dS_D} + \bar{K}\frac{dr_K}{dS_D} + \bar{L}\frac{dw}{dS_D} + \frac{dGT}{dS_D}\right) \qquad \text{A.8}$$

Using the first-order conditions, the first two terms on the right collapses to zero. We also divide through by λ to arrive at the following.

$$\frac{1}{\lambda}\frac{dU}{dS_D} = \bar{R}\frac{dr_R}{dS_D} + \bar{K}\frac{dr_K}{dS_D} + \bar{L}\frac{dw}{dS_D} + \frac{dGT}{dS_D} - F_L\frac{dP_L^C}{dS_D} - F_D\frac{dP_D^C}{dS_D} - \frac{u_z}{\lambda}\frac{dZ}{dS_D} \qquad \text{A.9}$$

Using the consumer prices expressed in terms of producer prices in section 3.0, we simplify the following expressions

$$-F_{LS}\left(\frac{\partial MC_F}{\partial P_G^c}\frac{dP_G^c}{dS_D} + \frac{\partial MC_F}{\partial P_E^c}\frac{\partial P_E^c}{\partial S_D}\right) - F_{DS}\left(\frac{\partial MC_D}{\partial P_D^c}\frac{dP_D^c}{dS_D}\right)$$

$$-F_{LS}\left(\frac{\partial MC_F}{\partial P_G^c}\frac{d(P_G^P+tg)}{dS_D}+\frac{\partial MC_F}{\partial P_E^c}\frac{\partial(P_E^c-S_E)}{\partial S_D}\right)-F_{DS}\left(\frac{\partial MC_D}{\partial P_D^c}\frac{dP_D^c}{dS_D}\right)$$

We apply producer prices expressed in terms of marginal cost functions, and we submit them into (A.9)

$$\frac{1}{\lambda}\frac{dU}{dS_D}=\bar{R}\frac{dr_R}{dS_D}+\bar{K}\frac{dr_K}{dS_D}+\bar{L}\frac{dw}{dS_D}+\frac{dGT}{dS_D}-F_{LS}\left(\frac{\partial MC_F}{\partial P_G^c}\frac{d(P_G^P+tg+tc)}{dS_D}+\left(\frac{\partial MC_F}{\partial P_E^c}\left(\frac{\partial MC_E}{\partial P_D^c}\frac{\partial P_D^c}{\partial S_D}+\frac{\partial MC_E}{\partial r_K}\frac{dr_K}{dS_D}+\frac{\partial MC_E}{\partial w}\frac{dw}{dS_D}\right)-\frac{dS_E}{dS_D}\right)\right)-F_{DS}\left(\left(\frac{\partial MC_D}{\partial r_R}\frac{dr_R}{dS_D}+\frac{\partial MC_D}{\partial r_K}\frac{dr_K}{dS_D}+\frac{\partial MC_D}{\partial w}\frac{dw}{dS_D}\right)-\frac{dS_D}{dS_D}\right)+F_E\frac{dP_D^C}{dS_D}+F_X\frac{dP_D^C}{dS_D}+\frac{u_z}{\lambda}\frac{dZ}{dS_D} \qquad \text{A.10}$$

We substitute the market equilibrium conditions for the ethanol and gasoline markets, apply Shepherd's lemma on the supply market expressions, and differentiate the government constraint and the pollution function with respect to the feedstock subsidy, expressing import and export prices in terms of world market prices, and obtain the following. Note: $P_G^P=P_G^W+tm,\ P_D^C=P_D^W$

$$\frac{1}{\lambda}\frac{dU}{dS_D}=\bar{R}\frac{dr_R}{dS_D}+\bar{K}\frac{dr_K}{dS_D}+\bar{L}\frac{dw}{dS_D}+tm\frac{dG_M}{dS_D}+tg\frac{dG_D}{dS_D}+t_c\frac{dE_D}{dS_D}+t_e\frac{dE_D}{dS_D}-F_S-S_D\frac{dF_S}{dS_D}-S_E\frac{dE_D}{dS_D}-G_M\frac{d(P_G^W+tm+tg)}{dS_D}-E_D\left(\frac{F_E}{E_S}\frac{\partial P_D^c}{\partial S_D}+\frac{K_E}{E_S}\frac{dr_K}{dS_D}+\frac{L_E}{E_S}\frac{dw}{dS_D}\right)-F_S\left(\left(\frac{R_F}{F_S}\frac{dr_R}{dS_D}+\frac{K_F}{F_S}\frac{dr_K}{dS_D}+\frac{L_F}{F_S}\frac{dw}{dS_D}\right)-\frac{dS_D}{dS_D}\right)+F_E\frac{dP_D^C}{dS_D}+F_X\frac{dP_D^W}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dS_D} \qquad \text{A.11}$$

Considering that $E_D=E_S$, and rearrange leading us to the following

$$\frac{1}{\lambda}\frac{dU}{dS_D}=\bar{R}\frac{dr_R}{dS_D}+\bar{K}\frac{dr_K}{dS_D}+\bar{L}\frac{dw}{dS_D}+tm\frac{dG_M}{dS_D}+tg\frac{dG_D}{dS_D}+t_e\frac{dE_D}{dS_D}-F_S-S_D\frac{dF_S}{dS_D}-S_E\frac{dE_D}{dS_D}-G_M\frac{dP_G^W}{dS_D}-G_M\frac{dtm}{dS_D}-G_M\frac{dtg}{dS_D}-\left(F_E\frac{\partial P_D^c}{\partial S_D}+K_E\frac{dr_K}{dS_D}+L_E\frac{dw}{dS_D}\right)-F_S\left(R_F\frac{dr_R}{dS_D}+K_F\frac{dr_K}{dS_D}+L_F\frac{dw}{dS_D}-1\right)+F_E\frac{dP_D^C}{dS_D}+F_X\frac{dP_D^W}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dS_D} \qquad \text{A.12}$$

$$\frac{1}{\lambda}\frac{dU}{dS_D}=\bar{R}\frac{dr_R}{dS_D}+\bar{K}\frac{dr_K}{dS_D}+\bar{L}\frac{dw}{dS_D}+tm\frac{dG_M}{dS_D}+tg\frac{dG_D}{dS_D}+t_c\frac{dE_D}{dS_D}+t_e\frac{dE_D}{dS_D}-F_S-S_D\frac{dF_S}{dS_D}-S_E\frac{dE_D}{dS_D}-G_M\frac{dP_G^W}{dS_D}-G_M\frac{dtm}{dS_D}-G_M\frac{dtg}{dS_D}--F_E\frac{\partial P_D^c}{\partial S_D}-K_E\frac{dr_K}{dS_D}-L_E\frac{dw}{dS_D}-R_F\frac{dr_R}{dS_D}-K_F\frac{dr_K}{dS_D}-L_F\frac{dw}{dS_D}+F_S+F_E\frac{dP_D^C}{dS_D}+F_X\frac{dP_D^W}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dS_D} \qquad \text{A.13}$$

Using the full employment condition in factor markets and crossing out terms yields

$$\frac{1}{\lambda}\frac{dU}{dS_D}=tm\frac{dG_M}{dS_D}+tg\frac{dG_D}{dS_D}+t_e\frac{dE_D}{dS_D}-S_D\frac{dF_S}{dS_D}-S_E\frac{dE_D}{dS_D}-G_M\frac{dP_G^W}{dS_D}-G_M\frac{dtm}{dS_D}-G_M\frac{dtg}{dS_D}+F_X\frac{dP_D^W}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D}-\frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dS_D} \qquad \text{A.14}$$

We assume that $\frac{dtm}{dS_D} = 0, \frac{dtg}{dS_D} = 0$. Furthermore, adding and subtracting $P_G^W \frac{dG_M}{dS_D}$ from $G_M \frac{dP_G^W}{dS_D}$, and $P_D^W \frac{dF_X}{dS_D}$ from $F_X \frac{dP_D^W}{dS_D}$, allows us to obtain the world import supply elasticity of gasoline and export demand elasticity of food. We also rearrange to get the final expression A.15. This expression is applied in the policy analyses. In each case, adjustments are made, and irrelevant terms dropped accordingly.

$$\frac{1}{\lambda}\frac{dU}{dS_D} = tm\frac{dG_M}{dS_D} + tg\frac{dG_D}{dS_D} + t_e\frac{dE_D}{dS_D} - S_D\frac{dF_S}{dS_D} - S_E\frac{dE_D}{dS_D} - G_M\frac{dP_G^W}{dS_D} + F_X\frac{dP_D^W}{dS_D} - \frac{u_z}{\lambda}\frac{dZ}{dFL}\frac{\partial FL}{\partial G_D}\frac{dG_D}{dS_D} - \frac{u_z}{\lambda}\frac{dZ}{dF_L}\frac{\partial F_L}{\partial E_D}\frac{dE_D}{dS_D} \qquad \text{A.15}$$

Considering that all the subsidies are counter financed by increasing the tax t_g on gasoline, and the on tax on gasoline when used as a policy tool is also counterbalanced by a tax on ethanol, we use the terms $t_g \frac{dG_D}{dS_D}$, $t_g \frac{dG_D}{dS_E}, and\ t_e \frac{dE_D}{dt_g}$ to derive the interaction and revenue recycling effects of the respective counterbalancing policy tools:

$t_g \frac{dG_D}{dS_D} = t_g \frac{\partial G_D}{\partial P_F}\frac{dP_F}{dS_D} + t_g \frac{\partial G_D}{\partial t_c}\frac{dt_c}{dS_D}$ *-feedstock subsidy*

$t_g \frac{dG_D}{dS_E} = t_g \frac{\partial G_D}{\partial P_E}\frac{dP_E}{dS_E} + v\frac{\partial G_D}{\partial t_c}\frac{dt_c}{dS_E}$ *-ethanol subsidy*

$t_e \frac{dE_D}{dt_g} = t_e \frac{\partial E_D}{\partial P_g}\frac{dP_g}{dt_g} + t_e \frac{\partial E_D}{\partial t_e}\frac{dt_e}{dt_g}$ *-gasoline tax*

By rearranging and collecting like terms, we arrive at the equations 22 – 25 of section 3.0.

Appendix C

C1. Derivation of an equivalent feedstock subsidy rates

Feedstock subsidy rate

Using the formula for the link between the corn and ethanol price by de Gorter and Just (2009), the price of feedstocks in shillings per kg PFD_{KG} of maize is given by:

$$PFD_{KG} = \frac{\beta}{1-\delta}(PE - s) \qquad \text{C.1}$$

Where β is the liters of ethanol from 1 kg of corn, δaccounts for by-products, and $PE - s$ is the price of ethanol less the subsidy. We assume constant processing costs, and we also drop the parameter of by-products such that:

$$PFD_{KG} = \beta(PE - s) \qquad \text{C.2}$$

The production coefficients of maize, cassava, and sugarcane ethanol translate into 2.69, 2.63, and 12.5 kgs per liter of ethanol, respectively [23]. We, therefore, obtain the following price relations for maize, cassava, and sugarcane ethanol in equations C.3, C.4, and C.5.

$PFD_{KG,maize} = 0.37(PE - s)$ C.3

$PFD_{KG,cassava} = 0.38(PE - s)$ C.4

$PFD_{KG,sugarcane} = 0.08(PE - s)$ C.5

We then use the coefficients in equations C.3, C.4, and C.5 multiplied by the subsidy rate on the common price of ethanol of 0.33 to obtain the corresponding feedstock subsidy rate for each.

Therefore, we arrive at 0.121, 0.124, and 0.026 for maize, cassava, and sugarcane ethanol.

C2. **The offsetting reduction in the ethanol tax for the gasoline tax policy**

The normalized price in the SAM for ethanol, inclusive of all taxes, is 2.30 and 1.90 for gasoline.

We relate the two prices as

$=$ C.6

$2.30 = \gamma \ 1.90$ C.7

Therefore, the percentage reduction in the tax on ethanol is equivalent to the percentage increase in the tax on gasoline multiplied by γ, which is approximately 0.498. We kept adjusting until the adequate volume of ethanol was generated.

C3. The ethanol production subsidy rate

We applied a rate equal to the ethanol consumption subsidy rate of 0.33.

[23] The feedstock coefficients and ethanol subsidy rate are adopted from Nakamya and Romstad (2020).

Paper III

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How sustainable are biofuels in a natural resource-dependent economy?

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ABSTRACT

For biofuels to promote growth in low-income agriculture-dependent economies, sustainability should be at the forefront of their biofuel programs. The high dependence on natural resources exposes such economies to resource misuse and environmental mismanagement risks. This research uses the case study of Uganda to assess the land, energy, water, and carbon footprints of maize, cassava, and sugarcane ethanol. All three pathways have positive energy balances, and the carbon footprints range between 0.89–3.12, 0.85–2.19, and 0.24–0.49 kg CO2eq/L of maize, cassava, and sugarcane ethanol, respectively. It would take about 15 years for maize ethanol, 14 for cassava ethanol, and 6 for sugarcane ethanol to break even with reference to gasoline if feedstocks were produced on converted grassland. Sugarcane ethanol is superior to maize and cassava ethanol, and its benefits derive from the carbon-neutral co-product electricity and a relatively higher ethanol yield per hectare. The study findings flag the ethanol processing stage and feedstock farming as key emission hotspots. They also reflect the emissions-reducing potential of ethanol exhibited by a decline in national emissions. Land requirements are minimal, and this demand diminishes with the improvement in crop yields. Overall, there are high prospects of economic and environmental gains. However, agricultural investment and immediate attention to poor crop yields are required alongside a regulated framework and the promotion of low-carbon energy sources.

Introduction

The production and consumption of liquid biofuels, such as ethanol and biodiesel, presents enormous potential in addressing climate change and fostering energy security, agricultural diversification, and rural development. Biofuels can provide a new model for poverty alleviation and economic development to low-income agriculture-dependent economies. For instance, positive prospects ranging from an improved trade balance (Nakamya & Romstad, 2020) to improved socio-economic well-being through employment, agricultural market expansion, and enhanced household income have been reported (Hartley et al., 2019; Portale, 2012). From the environmental point of view, carbon sequestration during feedstock growth and the displacement of fossil fuels may significantly reduce greenhouse gas (GHG) emissions, contributing to climate change mitigation.

However, other research has also revealed how the production and consumption of biofuels is by no means without complex and adverse effects. The above benefits may be realized at the expense of high food prices, mainly hurting the food poor who are typical of developing countries. Moreover, the increase in demand for crops may expand land usage to areas with high carbon stocks, inducing land-use change (LUC) emissions[1] (Acheampong et al., 2017; Fargione et al., 2008; Searchinger et al., 2008). Additional emissions may also be generated through changes in farming practices and increased use of fertilizer and other inputs. Other environmental impacts such as excessive water use and biodiversity loss may also occur.

Despite the trade-offs highlighted above, the impacts of biofuels across different settings cannot be generalized because of the disparities in production systems, livelihood sources, feedstock types, soil carbon contents, and overall geographical conditions. Nonetheless, these trade-offs point to significant implications, particularly for the natural resource-dependent economies. Typically, these economies rely on natural resources for their livelihood, making them more vulnerable to resource misuse and climate change. Therefore, such circumstances compel rigorous research on green growth, land requirements and availability, water requirements, and other environmental aspects when considering biofuel investments.

Several studies underscore the socio-economic benefits of biofuels (see Campbell et al., 2016; Gebreegziabher et al., 2018; Hartley et al., 2019; Huang et al., 2012; Nakamya & Romstad, 2020; Portale, 2012; Zilberman et al., 2013). While this line of research provides valuable insights, it does not fully capture other sustainability aspects of certain activities along the biofuel supply chain. In contrast, Life Cycle Analyses

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

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(LCA) focus on environmental aspects, such as energy and carbon footprints. For example, Seabra et al.'s (2011) well-to-wheels analysis; Wang et al.'s (2012) evaluation of US corn and Brazil's sugarcane ethanol; the full life cycle assessment by the Environmental Protection Agency (EPA, 2010) for biofuels projections under the Regulatory Impact Analysis Renewable Fuel Standard Program (RFS2); and the study by Lewandrowski et al., 2019 which drew on the EPA (2010) report with more updated data. Baumert et al. (2018) conducted an LCA of Jatropha biodiesel in Burkina Faso, and Fernández-Tirado et al. (2016) compared the environmental burden of biodiesel in Spain from locally produced rapeseed and Argentinean imported soybean oil. Other LCAs estimate the water footprint (Demafelis et al., 2020; Gheewala et al., 2013; Kaenchan & Gheewala, 2017; Wu et al., 2009). Mekonnen et al. (2018) examined US corn and Brazil sugarcane ethanol's energy, water, and carbon footprints, while Ghani et al. (2019) quantified the energy, water, carbon, and ecological footprints of molasses-based ethanol in Pakistan.

While the above two strands of research are more complementary than competitive, the analyses are vastly different and independent. Rational and effective biofuel policies should consider all the pillars of sustainability (Nazari et al., 2020). However, only a handful of studies have taken the approach of simultaneously investigating socio-economic and environmental impacts; for example, Obidzinski et al., 2012; Thurlow et al., 2016; and Schuenemann et al., 2017. Obidzinski et al. analyzed the socio-economic and environmental impacts of palm oil development for biofuels in Indonesia. They found positive economic gains that were unevenly distributed as well as deforestation and other perceived ecological effects. Their research, however, does not quantify the environmental burden per unit of the biofuel, which would be of relevance, for example, in setting certification standards. Taking a different approach, Iddrisu and Bhattacharyya (2015) forecast transport fuel demand to assess the viability of Ghana's biofuel target of a 20% share and the required inputs. They conducted a detailed analysis that offers valuable insight into biofuel potential and challenges in developing countries, but their study scope did not capture some environmental aspects. Moreover, the interconnectedness of biofuels with other sectors in the economy makes price and activity adjustments crucial determinants of the final impacts; hence, the need for a holistic model. Thurlow et al. and Schuenemann et al. took this approach and used an integrated modeling framework with a computable general equilibrium (CGE) model. The former focuses on socio-economic impacts, GHGs, and land, while the latter extends the assessment to water use. However, they both restricted the evaluation to one biofuel type, sugarcane ethanol, and large volumes for exports.

There is still a need to investigate biofuel impacts, taking into account economic adjustments and the entire supply chain. Second, an evaluation of attainable production targets for home consumption could be essential, particularly at the initial stages of the biofuel industry. Third, I am unaware of any broad and simultaneous analysis of multiple feedstocks from a sustainability perspective, particularly in developing countries. Moreover, no carbon or other footprints have been estimated for the suggested feedstocks in Uganda's biofuel programs.

Therefore, this study seeks to close this gap. It builds on the above literature by conducting a comparative evaluation of maize, cassava, and sugarcane ethanol, with emphasis on land requirements and the environmental sustainability of the three ethanol pathways. This is achieved by answering the following research questions. How energy efficient is the ethanol from maize, cassava, and sugarcane? What is the water footprint of each ethanol pathway? To what extent can ethanol reduce GHG emissions relative to gasoline, and what is the impact on overall emissions? How much land is required in proportion to the total available agricultural land?

The research uses the case study of Uganda, a low-income and natural resource-dependent economy. It follows a two-step approach to Consequential Life Cycle Assessment (CLCA) in a recursive dynamic Computable General Equilibrium Model (CGE). The model is calibrated to the 2016/17 Uganda social accounting matrix (SAM), incorporating maize, cassava, and sugarcane ethanol. A volume adequate for a 10% blending within 15 years is simulated. Despite the planned 20% blend target by the Ministry of Energy and Mineral Development (MEMD), the current vehicle fleet can run on a 10% blend without major engine or fuel system modifications. Moreover, a higher blending level for an infant ethanol industry may not be realistic or feasible. The modeling approach allows the assessment of cumulative emissions and determining a carbon payback period under land-use change scenarios. This is fundamental in decisions regarding the pathways that minimize the negative impacts. The results shed light on the hotspots along the ethanol supply chain, which can be targeted for improvement to ensure a sustainable ethanol industry. Furthermore, the research contributes to the meager literature on the sustainability of biofuels, especially in Africa.

Uganda presents a suitable case study of a low-income and natural resource-dependent economy. The average contribution of agriculture to total GDP is about 24%, with over 65% of the working population engaged in agriculture (Uganda Bureau of Statistics (UBOS), 2018). There has been continuous government effort toward value-added agriculture to improve farmers' returns and strategies to reduce vulnerability to climate change through adaptation and mitigation measures; the government has yet to deliver on these. As one of the strategies to curb climate change, the country is at the initial stages of designing and implementing biofuels and climate change policies. A biofuels act was passed in 2018 to regulate biofuel production, distribution, and consumption. This was followed by a Biofuels General Regulations draft of 2020 to guide the initial blending of 5% for ethanol and biodiesel.[2] Moreover, a fuel blend of up to 20% is one of the Biomass Resource Management Investment Priorities for 2020/21 (MEMD, 2020), but this has not been achieved. Regarding the climate change policy, a 22% reduction of the overall national GHG emissions by 2030 is anticipated from the suggested climate change adaptation and mitigation strategies in the Nationally Determined Contribution (INDC) (Ministry of Water and Environment (MWE), 2015).

MEMD identified cassava and sugarcane as some of the candidate ethanol feedstocks. Although maize was not included, information from the field visits revealed it as a primary raw material besides sugarcane in the current production of Extra Neutral Alcohol. The average contribution of cash crops to Uganda's GDP is about 2%, while the food crop subsector accounts for about 13%. In terms of production and area planted, maize and cassava come in close second and third positions, respectively, after plantain banana among Uganda's 16 major food crops. Sugarcane is also a significant cash crop (Uganda Bureau of Statistics (UBOS), 2020a,b). According to Uganda's Annual Agriculture Survey of 2018, maize is cultivated by over 55% of the agricultural households while 29% grow cassava (Uganda Bureau of Statistics (UBOS), 2020b). On this account, maize, cassava, and sugarcane were selected for this analysis.

The rest of the paper is organized as follows: Section two presents the methods and data. Section three reports the results, four provides a comparative discussion, and five ends with the conclusion and policy implications.

Methods and data

The economy-wide model

The interconnectedness of biofuels with other sectors and the tradeoffs involved warrant considering all the related industries and the entire biofuel supply chain (Azapagic et al., 2017). This study follows a two-step approach to consequential life cycle analysis (CLCA), according to Yang (2016), to quantify the energy, water, and emissions associated with the ethanol supply chain, taking into account activities and market adjustments. CLCA entails assessing the environmental burdens of a product system, including activities expected to change due to a change in demand in the functional unit (Sonnemann et al., 2011). Because of the interlinkages, ethanol production can alter the production

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

levels of other activities, and the substitution of ethanol for imported gasoline may cause changes in the trade balance. Therefore CLCA in a CGE framework, rooted in general equilibrium theory, is a suitable approach to modeling the environmental aspects of ethanol while considering the adjustment in markets and related activities (Rajagopal, 2017).

This study adapts the PEP-1-t single-country recursive dynamic CGE by Decaluwé et al. (2013).[3] The model is calibrated to the SAM by Nakamya and Romstad (2020), a modified version of the 2016/17 Uganda official SAM developed by Tran et al. (2019). The original SAM was from the Ministry of Finance, Planning, and Economic Development. Data on gasoline imports and prices were obtained 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.

Nakamya and Romstad introduced an ethanol sector based on maize, cassava, sugarcane, and molasses.[4] The current study adopts this model structure and introduces dynamic equations by updating certain exogenous variables (see Supplementary material (SM) Appendix A). This allows to capture the transitional path and to track ethanol impacts over the entire period. In particular, labor, land, total factor productivity, the autonomous element of household consumption, recurrent government expenditure, and capital accumulation are updated by policy-independent changes to form the baseline scenario as described under Section 2.3.[5]

The model comprises 34 activities and commodities, 8 household categories, 16 labor types, capital, cropland, firms, and the government. Production sectors combine aggregate value-added and aggregate intermediate inputs in a Leontief production function. A similar functional relation governs the individual intermediate inputs into the aggregate intermediate for all the sectors, except the Ethanol-blending industry, which uses a constant elasticity of substitution (CES) function. Components of the value-added and the labor and capital composites also apply a CES, allowing factor substitution driven by relative prices.

The model allows the production of more than one commodity by a given sector, combined in a constant elasticity of transformation (CET) function. Therefore, the ethanol sectors produce co-products that are part of other commodity categories. For instance, Distillers Grains from cassava and maize ethanol enter the animal feed sector while bagasse electricity goes to the industry with 'Other electricity.' Substitution between ethanol and the co-products is assumed to be highly inelastic.

Domestic output is allocated to the local and export markets under the assumption of imperfect substitutability using a CET function. Conversely, the Armington function allocates domestic absorption between domestic output and imports. Absorption comprises household consumption, public demand, investment demand, intermediate demand, and the demand for margin services. Uganda is a small economy relative to the global market; hence, world import and export prices are exogenous. The model, however, 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.

Households earn income from factor endowment and transfers. They spend it on savings, taxes, and consumption, modeled as linear expenditure systems derived from the maximization of a Stone-Geary utility function. The key elasticity parameters of all the functions are presented in SM Appendix A, Table A.1.

Land and labor are mobile across sectors, growing at constant rates as elaborated in the baseline projection under Section 2.3. The supply of total 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, earning sector-specific rents.

Total investment is a function of savings by the households, firms, and the government plus foreign borrowings. It comprises gross fixed capital formation and changes in stocks, where the former is a sum of both private and public investment expenditure. The savings-investment balances are savings-driven, with investment endogenous. The consumer price index is the model numeraire. The current account is fixed with a flexible real exchange rate as the equilibrating variable. The government receives non-tax income from the rest of the world plus revenues from taxes on household and firm incomes, products, and production activities. Its savings are a flexible residual between revenues and expenditure (fixed), and all the tax rates are exogenous.

The energy and environmental module (two-step approach)

The equations and the detailed calculations pertaining to this section are presented in SM Appendix A.

Goal and scope

The goal of this module is to assess the energy, water, and carbon footprints of maize, cassava, and sugarcane ethanol. It also compares land requirements for all three ethanol pathways.

The aim is to provide first insights into Uganda's ethanol environmental impacts and identify the primary sources of the environmental burden. The findings are open to scrutiny and debate. They should be treated as one point of evidence for consideration in Uganda's biofuels and climate change strategies, such as the 22% emissions reduction by 2030 as envisioned in the NDC (MWE, 2015). The analysis captures an attributional life cycle assessment (ALCA) in the first stage and a consequential life cycle assessment (CLCA) in the second through scenarios and associated processes and market changes.

In the ALCA part, the system boundary includes feedstock farming, transportation, processing, ethanol transportation and distribution, and fuel combustion; hence, a well-to-wheels analysis (Singh et al., 2010). The functional unit is a liter of fuel, based on which per-liter energy use in megajoules (MJ), carbon emissions in kg CO2eq, and water use in liters (L) are determined and compared. The ALCA is used to identify hot spots (Weidema, 2003) and as a basis for the baseline scenario. In the CLCA part, the simulation of the 0.19 billion liters of ethanol involves two general cases of direct land-use change.

The conversion factors, emission coefficients, energy, and water-related parameters are recorded in Table 1.

The energy footprint

The energy footprint assesses energy consumed in producing a product within a specified system boundary. The energy footprint (EF_e) of ethanol type *e* is the sum of the direct energy input at every production stage minus energy allocated to the co-product ($E_{co-products}$) in the ethanol production system.

$$EF_e = E_{farming} + E_{transport} + E_{processing} + E_{distribution} - E_{co-products} \quad (1)$$

Every term in Eq. (1) is expressed in MJ[6]/L of ethanol. $E_{farming}$ is the energy consumed in feedstock farming, comprising the energy in labor and fuels used in plowing and planting. Plowing is done for all feedstocks, while mechanized planting is for sugarcane only. Both activities occur once at a fuel consumption rate of 15 L per hectare for each activity. Labor energy is derived from labor requirements calculated as man-hour per hectare. The number of

[3] The model was run in GAMS.

[4] Molasses is dropped in the current study.

[5] For further modifications of the model such as the characterization of the investment demand function and total investment distribution please refer to Decaluwé et al. (2013).

[6] Energy content at Lower heating value of 21.1 MJ/L is adopted.

Table 1
Parameters used in the ethanol LCA analysis.

Maize		
Maize yield	2.2 t/ha[a]	
Maize ethanol yield	370 L/t[b]	
Labor days per hectare	127[m]	
Fertilizer application rate/ha (3%)[d]	gCO2-eq/kg of fertilizer	kgs of fertilizer/ha
NPK 15-15-15	4987.90[c]	100.00[d]
Urea	3556.12[c]	50.00[d]
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1563.35[c]	75.00[d]
Feedstock transportation	100KM	
Energy in processing	11.12 MJ/L[k]	
Ethanol distribution	200KM	
Converted grassland	26tco2/ha[f]	
Cassava		
Cassava yield		3.2 t/ha[a,*]
Cassava ethanol yield		380 L/t[b]
Labor days per hectare		287[n]
Feedstock transportation		100KM
Energy in processing		11.12 MJ/L[k]
Ethanol distribution		200KM
Converted grassland		26tco2/ha[f]
Sugarcane		
Sugarcane yield	60 t/ha[g]	
Sugarcane cane ethanol yield	80 L/t[h]	
Labor days per hectare	325[p]	
Fertilizer application rate/ha (77%)[d]	gCO2-eq/kg of fertilizer	kgs of fertilizer/ha
NPK 15-15-15	4987.90[c]	100.00[d]
Urea	3556.12[c]	160.00[d]
Di-Ammonium-Phosphate (DAP) 18%N 46%P2O5	1563.35[c]	117.00[d]
Muriate of Potash (MOP) 60%K2O	413.83[c]	20.00[d]
Rock phosphate 21%P2O5 23%SO3	95.00[c]	15.00[d]
Triple superphosphate (TSP)	545.76[c]	50.00[d]
Feedstock transportation	50KM	
Energy in processing	1.69MJ[j]	
Ethanol distribution	200KM	
Converted forest land	26tCO2/ha[f]	
	151 tCO2/ha[f]	
Carbon sequestration	4.1 tCO2/ha[e]	
Foregone forest carbon sequestration	5.68 t CO2eq/ha/year	

Note: *The cassava yield is expressed in terms of dried cassava chips using a conversion factor of 2.4 kg/kg (Kuiper et al., 2007).
Parameter source:
[a] UBOS (2016).
[b] Vinh (2003).
[c] Standard calculation values.v.1.0 https://ec.europa.eu/energy/sites/ener/files/documents/Standard%20values%20v.1.0.xlsx. These are adjusted with the latest global warming potential 1, 28, 265 for Co2, CH_4, $N2_O$, respectively.
[d] Godfrey and Dickens (2015).
[e] Thurlow et al. (2016).
[f] EPA (2010) report page 391 for forest and 393 for grassland.
[g] FAO (2020).
[h] Shumba et al. (2011) and Hartley et al. (2019).
[j] Seabra et al. (2011).
[k] Pimentel and Patzek (2005).
[m] Shepherd (2010).
[n] Fermont et al., 2010.
[p] Sharma and Prakash (2011).

labor days needed per hectare was converted to hours per hectare using a rate of 8 h of work per day, whose caloric equivalent[7] is expressed in MJ using a factor of 2.3 MJ per man-hour (see Fluck, 2012).

The energy balance or net energy (NE_e) from the energy footprint is determined as the difference between the energy content of ethanol (E_e)and the energy footprint (EF_e).

$$NE_e = E_e - EF_e \tag{2}$$

A net energy ratio (NER) of energy output to total energy input is also obtained in Eq. (3). This measures the amount of energy produced (by ethanol) per unit of energy used; a ratio greater than one implies net usable energy gains from ethanol.

$$NER_e = \frac{E_e}{EF_e} \tag{3}$$

The carbon footprint

Three scenarios are considered for carbon quantification. As described earlier, Scenario 1 is a typical ALCA, estimating carbon emissions at every stage of the supply chain. The stages include feedstock farming, transportation, processing, ethanol transportation and distribution, and fuel combustion. The life cycle inventory stage considers only direct emissions associated with direct inputs.[8] The CGE model is run with a constrained land supply, only growing at a constant rate. No land expansion occurs except the possible displacement of some crops, such as beans, soybean, and bananas (matooke), whose soil organic carbon (SOC) changes and carbon sequestration are considered minuscule. And if any, the emission levels would still lie below the upper bound of the extreme cases with LUC.

Emissions from the farming stage are attributed to fuel consumption during plowing for all three feedstocks and planting for only sugarcane. This assumption is justified by the high labor-intensive farming practices in Uganda. The stage also accounts for fertilizer application emissions in maize and sugarcane farming as it is uncommon for Ugandan farmers to use fertilizers in cassava growing (Fermont et al., 2010).

Fertilizer emissions are determined according to Uganda's current fertilizer application rates, calculated from the study by Godfrey and Dickens (2015). The types of fertilizers 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 determine the actual quantities of feedstock and the corresponding hectares required to produce it. Fertilizer application rates are then used to calculate the area fertilized for each crop. Based on the crop acreage, the amount of fertilizer per hectare, and the crop and ethanol yeilds, fertilizer emissions per liter of ethanol are derived using the relevant emission factors.

Emissions from feedstock transportation to processing sites are based on a 100 km distance for maize and cassava and 50 km for sugarcane. Transportation of all feedstock types assumes a truck with a 20-metric ton carrying capacity and fuel consumption of 0.4 L per kilometer.[9]

Ethanol processing requires steam and electric energy. Maize and cassava are starch feedstocks; hence, their ethanol processes are assumed to be similar. The steam used in maize and cassava ethanol is assumed to be generated by diesel-fired boilers,[10] and the electricity consumed in the process is hydro-based. Hydroelectricity emissions are considered insignificant; therefore, ignored.[11] Sugarcane ethanol

[7] It is assumed that it requires at least 9 kcal per minute in farming (see Wanjek, 2005).

[8] This may not have a significant impact on the results since most inputs are imported.
[9] The estimation assumes hired truck, hence, it does not consider return of an empty truck.
[10] This is intended to assume a worst-case scenario, however, the current production of extra neutral alcohol from maize uses bagasse in some production facilities.
[11] Kumar et al. (2011) report a range of 4–14 g co2eq/kwh.

uses bagasse-fired boilers for steam and bagasse electricity. Although this energy is included in the energy footprint, it is considered carbon neutral in the carbon footprint (Carvalho et al., 2019; EPA, 2010; Kiatkittipong et al., 2009). Therefore, the electricity surplus can be exported to the national grid, generating emission credit to sugarcane ethanol. The credit is a negative of the GHGs that would have been emitted by stand-by oil-based thermal plants dispatched as a last resort for system reliability.

Scenarios 2 and 3 are conducted in a CLCA framework, with a broader system boundary than ALCA and taking into account changes in the ethanol volume, gasoline consumption, feedstock production, and other activities. Scenario 2 involves LUC attributed to converted grassland and in Scenario 3 to forestland. In these two scenarios, the land constraint is released, and all land in the production of the feedstocks is either grassland (scenario 2) or forestland (scenario 3). The scenarios allow comparability across the three feedstocks as two of these are already suggested candidates by the MEMD. The simulations account for 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, with a carbon sequestration rate of 4.1 t CO2eq/ha/year maintained for both LUC scenarios.

The carbon stock value for grassland is 26 t CO2/ha and 151 t CO2/ha for forestland. In scenario 2, all feedstock is grown on converted grassland, while in scenario 3, only sugarcane is grown on deforested land. Additionally, in the simulations, the total land requirement is also determined.

Since ethanol production increases gradually, land conversion occurs in a phased manner causing a once-off carbon loss from each land clearance. Emissions from this carbon are then calculated based on the acreage, and once emitted, they decline progressively for each extra liter of ethanol produced. Foregone sequestration from deforested land is added to sugarcane ethanol emissions at a per liter rate, while sequestration by sugarcane is subtracted.

Gasoline is the reference fuel displaced by ethanol. Since all the gasoline is imported, its emissions are associated with transportation and tailpipe. Tailpipe emissions are calculated for all fuels as a fixed proportion per liter using the relevant emission factors. Carbon dioxide from ethanol combustion is assumed to be biogenic[12]; therefore, ethanol's tailpipe emissions account for only methane and nitrous oxide (EPA, 2010; Wang et al., 2012). Both gasoline and ethanol are distributed based on a 200 km distance in a 4000 L truck with fuel consumption of 0.4 L per kilometer.

Maize and cassava are non-perennial crops. Therefore, their carbon footprint in farming corresponds to the quantity of feedstock and the volume of ethanol produced per period. In contrast, sugarcane is perennial, taking between 18 and 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 and SM Appendix B for the calculations).

The water footprint

The water footprint quantifies and compares consumptive water use of the three ethanol pathways. The water dependence of each ethanol type is highlighted, and possible irrigation requirements are identified. The scope includes green water and blue water footprints in feedstock farming and ethanol processing. It excludes greywater, which is freshwater required to assimilate pollutants. The green water footprint refers to the volume of rainwater, while bluewater is the surface or groundwater consumed in producing a product (Chapagain et al., 2006; Hoekstra et al., 2011). Eq. 4 specifies the total water footprint (WF_e) for each ethanol type as the sum of rainwater in feedstock farming ($WF_{farming,\ green}$), bluewater in feedstock farming ($WF_{farming,\ blue}$), blue water in ethanol processing ($WF_{processing,\ blue}$) minus any green or blue water allocated to the co-product ($WF_{co-products,\ (green+blue)}$). Each term in Eq. (4) is expressed in liters of water per liter of ethanol (L/L).

$$WF_e = WF_{farming,green} + WF_{farming,blue} + WF_{processing,blue} - WF_{co-products,(green+blue)} \quad (4)$$

WF in feedstock farming is estimated from the crop water requirement using a crop model. It is calculated using the reference crop evapotranspiration, climate, crop type, and crop growth stages. This is stated in Eq. (5), measured in mm/day (and converted to mm/month).

$$ET_{crop} = kc * ET_0 \quad (5)$$

ET_{crop} is the crop water requirement or crop evapotranspiration, which refers to the volume of water a crop would consume if water were available. kc is the crop factor and ET_0 the reference crop evapotranspiration (usually a grass crop). ET_0 is estimated using the FAO recommended Penman-Monteith method, based on the Penman-Monteith Eq. (6)[13] and local climate data.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6)$$

where ET_0 is the reference evapotranspiration (mm/day), R_n net radiation at the crop surface (MJ/m^2/day), G soil heat flux density (MJ/m^2/day), T mean daily air temperature at 2 m height (°C), u_2 wind speed at 2 m height (m/s), e_s saturation vapor pressure (kPa), e_a actual vapor pressure (kPa), $e_s - e_a$ the saturation vapor pressure deficit (kPa), Δ slope vapor pressure curve (kPa/°C), and γ psychrometric constant (kPa/°C). Details are found in Allen et al. (1998). The Δ, γ, *and* e_s are derived from values provided in Allen et al. and based on local temperatures. Because of data limitations, e_a is calculated from the average monthly relative humidity.

The kc parameters are adjusted for the crop growth stages. Since ET_{crop} is expressed as water depth in mm, the total WF in farming is converted to water volume in cubic meters per hectare using a factor of 10.

$$WF_{farming}(\mathrm{m^3/ha}) = 10 * \sum_{g=1}^{g} ET_{crop} \quad (7)$$

where g refers to the growth stages.

$WF_{farming}$ (m^3/ha) is further converted to liters per liter of ethanol using the crop (feedstock) and ethanol yields to arrive at the expression in Eq. (4). Note that, up to this point, the calculations account for only green water in farming.

Maize and sugarcane growth parameters are obtained from Brouwer and Heibloem (1986). The approximate duration of the crop growth stages and kc parameters are found in Brouwer and Heibloem (Tables 7 and 8 p.15 & 17) for maize and (Table 12a p. 26) for sugarcane. Climate data is obtained from Weather-Atlas[14] and is compared with data from individual studies on Uganda.[15] The adjustments and calculations are presented in SM Appendix B.

Irrigation requirements

The irrigation water requirement is any blue water consumed in feedstock farming ($WF_{farming,\ blue}$). It is calculated as the difference between the crop water need and effective rainfall (ER).[16]

[12] This carbon dioxide is assumed to be recaptured during feedstock growth.

[13] The calculation for ETo were done in excel.

[14] Retrieved from: https://www.weather-atlas.com/en/uganda/kampala-climate.

[15] For example the study: Mubiru and Banda (2012). Monthly average daily global solar irradiation maps for Uganda: A location in the equatorial region. *Renewable energy*, *41*, 412-415.

[16] Effective rainfall is that part of the rain fall consumed by the crop; the volume of rain that is not a run-off or what is percolated deep past the crop roots.

That is, $WF_{farming,\ blue} = ET_{crop} - ER$. If $ET_{crop} > ER$, there is a need for irrigation and blue water consumption in farming. However, if $ET_{crop} < ER$, $WF_{farming,\ blue}$ is zero.

Allocation method applied to co-products in all footprints

The allocation of energy, carbon, and water footprints between ethanol and their co-products is based on the market-value approach. The market values are determined based on the average prices in the base year and the yield of the products. Distillers Grains (DGs) is the co-product for maize and cassava ethanol, while bagasse electricity is for sugarcane ethanol. The price for DGs is approximated by the cost of maize bran, a by-product of maize flour. The market-value approach is appropriate, particularly for maize and cassava ethanol co-products since these are mainly valued for their nutrition and caloric values other than their energy content. The same approach is applied to sugarcane ethanol in the default simulations but compared with the energy-content method in the scenario analysis.

Baseline projection, dynamic variable update, and policy simulations

The adopted CGE is neoclassical, but modified with labor market rigidities consistent with the structure of the Ugandan economy. Population grows at 3.2% in the baseline scenario, skilled and urban unskilled labor at 4%, rural unskilled labor at 2.2%, and total factor productivity growth is fixed at 2% annually. The higher growth rate for skilled labor is intended to mimic the steady improvement of education attainment (Wiebelt et al., 2018) alongside stagnant employment levels. It also depicts both unemployment and rural-urban migration for urban unskilled labor. These trends generate an annual growth rate in real GDP of about 4%.[17] 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.

Each ethanol type is virtually zero in the baseline equilibrium. For a better comparison, each pathway contributes an equal volume to the total ethanol produced. In the simulations, the stock of capital in the ethanol sector is exogenously and gradually increased as producers draw in other inputs until the volume adequate for a 10% blending is reached in 2031 (see Hartley et al., 2019; Thurlow et al., 2016). Based on the historical trend of gasoline consumption, about 1.94 billion liters[18] of gasoline are assumed by 2031. It would therefore require approximately 0.194[19] billion liters of ethanol. Taxes on ethanol are arbitrarily set 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.

Due to data limitations, it is challenging to account for, project efficiently, and link the current national GHG emissions to consumption and economic activity. In this respect, a simplified approach is taken using the emission intensity calculated as a ratio of total emissions to real GDP. While this may be a rather rudimentary method,[20] it facilitates the calibration and tracking of total emissions in the baseline and simulation scenarios. Therefore, variations in gasoline and ethanol emissions, as well as national emissions, are determined by comparing the baseline with the simulation equilibria.

[17] According to the Ministry of Finance Planning and Economic development Background to the Budget document of 2021/2022, Uganda's GDP growth rate has been relatively above 4% over a couple of years.

[18] This value was determined taking into account the current economic downturn due to Covid 19.

[19] Note that for ethanol volumes up to a 10% blend level permit an equivalence of the units of gasoline and ethanol (Macedo et al., 2008).

[20] The approach disregards any changes GHG emissions efficiencies over the projection period.

Table 2
Macroeconomic and sectoral impacts with grassland conversion.

Baseline results are annual growth rates, while simulations results are percentage deviations from the final base year values except for emissions

	Base	Simulation
Real GDP	4.00	0.10
Total agriculture	4.60	0.10
Land supply	3.20	0.07
Cash crops	5.20	−0.58
Grain seeds	4.50	−0.14
Maize	4.60	0.87
Cassava	4.40	0.85
Sugarcane	4.80	13.36
Gasoline	3.6[a]	−11.82[a]
Final fuel	0.04	−0.02
Emission inventory	136.18[b]	135.89[b]
Real exchange rate	–	−0.71

A negative real exchange rate depicts an appreciation of the local currency.
[a] These are percentage changes in the imported volume, not local production.
[b] Total emissions are in absolute values expressed in million metric tons of CO2eq. Corresponding values under deforestation are 136.30 MMT CO2 eq in the baseline and 136.04 MMT CO2 eq for the simulation.

Caveats to the analysis

The recursive dynamic CGE does not solve intertemporal optimization problems; rather, it is an adaptive model without the forward-looking behavior of individuals. Nevertheless, 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 module, some emissions, for example, from pesticides, are excluded due to data inadequacy. Nonetheless, the use of pesticides by Ugandan farmers is still limited.[21] The analysis also excludes emissions from processing inputs, such as enzymes and yeast. These are also expected to have a minor contribution to total emissions.[22] Lastly, the failure to account for the ratoon sugarcane crop[23] may misrepresent the fuel and fertilizer used. It is, however, expected that the findings can provide a reasonable clue on the nature of emissions and potential hotspots.

Results

Sectoral and macro results

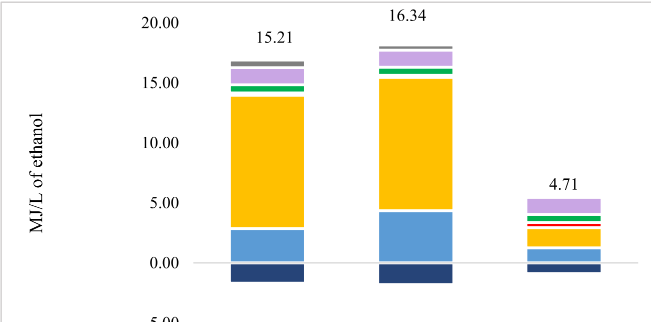
Table 2 reports the results of the variables relevant to the variations in emissions, and these are reported as percentage deviations from the final base year values unless otherwise stated. Because of an earlier publication on the socio-economic impacts, this analysis focuses on the environmental burden. Therefore, other findings on household income and the changes in welfare are presented in SM Appendix C.

The demand for feedstocks causes an increase in the flow of land, labor, and capital into the feedstock sectors, resulting in a corresponding growth in their output. As a result, the total land supply increases by 0.07%. However, because the land constraint is released in order to model LUC emissions, its rental rate is fixed. Moreover, the increase in the labor wage is marginal to cause a noticeable increase in the overall costs of production; nonetheless, the activities of some sectors, such as the "Cash crops" and "Grain seeds," decline. The impact on these sectors is primarily attributed to the appreciation of the exchange rate caused by declining gasoline imports. This lowers exports and reduces sectoral

[21] Uganda Bureau of Statistics (UBOS) (2020a, 2020b). The annual agriculture survey 2018 statistical release. Kampala Uganda. Uganda Bureau of Statistics.

[22] Dunn et al. (2012) find that enzymes and yeast contribute only 1.4% to the farm-to-pump GHG emissions in the production of starch ethanol.

[23] 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.



	Maize	Cassava	Sugarcane
Energy credit	-1.69	-1.82	-0.90
Farm mechanization	0.65	0.43	0.15
Blending	1.41	1.41	1.41
Distribution	0.68	0.68	0.68
transportation	0.18	0.18	0.43
Process	11.11	11.11	1.69
Labor	2.87	4.34	1.25
Energy footprint	15.21	16.34	4.71

Fig. 1. The energy footprint of maize, cassava, and sugarcane ethanol.

output, causing a decline in the demand for intermediate inputs, including fuel—for example, the demand for the final fuel declines, although marginally. Nevertheless, agricultural output and real GDP register positive growth, maintaining an upward trend in aggregate demand. Household income increases, and welfare improves for most households. These conditions drive the trend in total emissions. Overall, the impact of ethanol on national emissions is positive, contributing to a reduction between 0.26 and 0.29 million metric tons of CO2eq under grassland and deforestation, respectively.

Scenario 1 results

This section relates to the ACLA, estimating the relevant footprints without considering the impacts outside the ethanol system boundary.

Energy footprint

Fig. 1 depicts processing as the most energy-intensive stage for maize and cassava ethanol, constituting about 73 and 68% of the total energy requirements for maize and cassava ethanol, respectively. The two pathways also have significant labor-energy intensities per liter than sugarcane. Nonetheless, all three have positive energy gains with net energy balances of 5.89, 4.77, and 16.39 MJ/L and corresponding energy ratios of 1.39, 1.29, and 4.48 for maize, cassava, and sugarcane ethanol, respectively.[24]

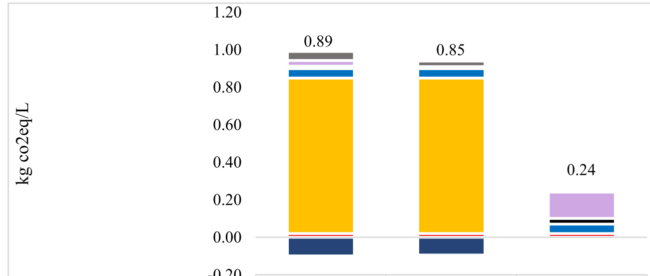
Carbon footprint excluding land-use

These results are presented in Fig. 2 and Table 3. Gasoline, the reference fuel, emits 2.33 kg CO2eq/L during combustion and 0.05 kg CO2eq/L in distribution; the latter is uniform across all fuels. Similar to the energy footprint, the processing stage is a significant source of GHGs, generating about 93 and 97% of the total emissions for maize and cassava ethanol, respectively. These are assumed to be zero for sugarcane ethanol.

Fertilizer emissions are higher in sugarcane farming than maize due to a higher fertilizer application rate (see Table 1). Nevertheless, mechanization emits more GHGs in maize and cassava farming because of the lower productivity per hectare. Similarly, emissions from feedstock transportation are high, especially for sugarcane.

Tailpipe emissions are uniform for all ethanol pathways, and so are transport and distribution emissions due to an assumed equal distance

[24] Energy content expressed at lower heating value of 21.1 MJ/L is used.



	Maize	Cassava	Sugarcane
Co-product credit	-0.10	-0.09	-0.01
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	0.24

Fig. 2. The carbon footprint of maize, cassava, and sugarcane ethanol without land-use change.

for all fuels. As shown in Fig. 2 and Table 3, co-products account for about 10% of the total emissions in maize and cassava ethanol. In comparison, this share is approximately 0.4[25] percent for the surplus electricity in sugarcane ethanol.

Scenario 2 results with LUC emissions

Per liter GHG emissions including LUC from converted grassland

Grassland conversion releases more carbon into the atmosphere, raising immediate total emissions to 29.15, 19.60, and 4.57 kgCO2eq/L for maize, cassava, and sugarcane ethanol, respectively. These are added to the emission profiles without LUC in Table 3. As observed in the final year values, total emissions per liter decline steadily as ethanol production increases (see Table 4). All ethanol types break even relative to gasoline in the reference period (15 years). This occurs when the cumulative emissions from ethanol equal gasoline emissions, as depicted in Fig. 3. Sugarcane, cassava, and maize ethanol breakeven in 6, 14, and 15 years, respectively. However, as observed in Fig. 3, emissions from all ethanol continue to fall, implying a payback period[26] beyond 15 years.

Per liter GHG emissions including LUC from deforested land

The conversion of forestland is limited to sugarcane growing and the immediate year emissions per liter of sugarcane ethanol are the highest in all the scenarios (see Table 5). Despite its emissions saving potential, sugarcane ethanol fails to reach a breakeven point under deforestation (see Fig. 4).

Ethanol and gasoline emissions

The long-run trend for gasoline demand remains positive because of the growth in commodity consumption. This causes a corresponding increase in its emissions but at a decreasing rate as gasoline is continuously displaced. A similar trend holds for the total emissions; however, these decline faster because per-liter emissions from ethanol are also falling. According to panel A of Fig. 5, total emissions (from ethanol and gasoline), which are initially higher, fall below gasoline emissions in 14 years. In Panel B, total emissions remain above gasoline emissions due to the high carbon release from deforested land. These findings coincide with a reduction in the approximated simulated national emissions portrayed in Table 2.

[25] Allocation based on the energy-content gives raise to a share of 39%.

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

Table 3
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	0.24	
Percentage reduction relative to gasoline	−62.61%	−64.29%	−89.92%	

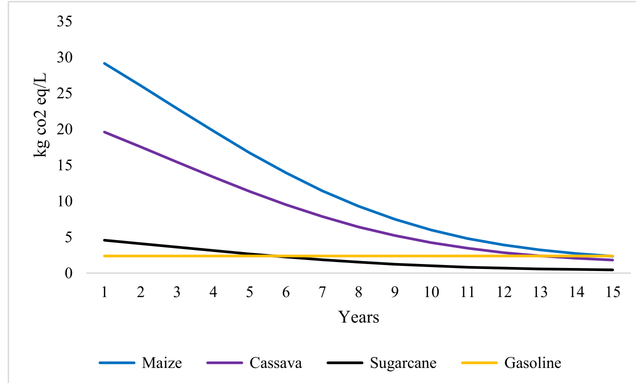


Fig. 3. Emissions per liter of ethanol and gasoline (All feedstock on 26 t CO2eq/ha grassland).

The water footprint and irrigation water requirement

Table 6 highlights the water requirements expressed in liters per liter of ethanol. Cassava ethanol has the highest consumptive water per liter, followed by maize and sugarcane ethanol. On the other hand, sugarcane has the highest water requirements per hectare owing to a longer growth period (18 months) and the actual monthly precipitation. Nevertheless, consumptive water per metric ton drops due to a higher per hectare yield (Fig. 6A). However, this is counterbalanced by a lower ethanol yield per metric ton (80 L/mt), making it the pathway with the highest per liter irrigation requirements (see Table 7 and Fig. 6B).

Despite cassava's higher water use, its irrigation water need is zero (see Table 7). This derives from the average precipitation in Uganda and the calculated effective rainfall over cassava's entire growth period, which exceeds its evapotranspiration.

Total land requirements

Based on the prevailing crop yields for the three feedstocks, approximately 144,724 ha of land would be required to produce the 0.19 billion liters of ethanol. Maize alone accounts for 55% of this land, with cassava and sugarcane constituting 36 and 9%, respectively.

Parametric and scenario analyses

Parameter sensitivity analysis is conducted with reference to scenario 2 results using a one-at-a-time approach by changing the critical input parameters of the life cycle inventory. Perturbation of the fertilizer application rates causes substantial changes in emissions (Table 8). This is mainly observed in maize because of a low crop yield. Variations in the process energy parameter also cause significant changes, especially for maize and cassava ethanol. This is as expected given the assumption of diesel-fired boilers. Similarly, the choice of the allocation methods substantially influences the findings. For example, the energy-based approach allocates more emissions to the co-product electricity than sugarcane ethanol, yielding higher carbon credits (see Table 8 and SM Appendix B).

Table 4
Scenario 2 - All feedstock cultivated on grassland with a carbon stock value of 26 t CO2eq/ha.

	Maize	Cassava	Sugarcane	Gasoline
Without LUC emissions but with co-product credits	0.89	0.85	0.24	2.38
Immediate year LUC emissions	31.40	20.83	5.36	
Carbon sequestration			−0.85	
Carbon credit from co-product (under LUC)	−3.14	−2.08	−0.18	
Immediate year total	29.15	19.60	4.57	
Final year value	2.34	1.82	0.45	
Percentage reduction relative to gasoline	−1.68%	−23.53%	−81.09%	

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

Varying the crop yield presents significant changes as well for land and crop water requirements. For example, a 50% increase in the crop yield for all feedstocks induces a reduction of about 33% in total land needed. As a result, land required drops from 144,724 to about 96,965 ha for the same volume of ethanol. Similarly, the irrigation water requirement for sugarcane drops substantially, and it is eliminated for maize, as depicted in Fig. 7.

Discussion of results and comparison with previous studies

The analysis highlights the processing stage as the most energy-intensive, especially for maize and cassava ethanol. Maize and cassava are starch-based[27] with a longer process before fermentation, which increases inputs consumption, including energy. Additionally, these have a high labor-energy intensity per liter of ethanol, deriving from lower crop yields and higher labor requirements in feedstock production. Nonetheless, the positive energy ratios point to prospects of energy gains. It is also noticed that the energy footprint for maize ethanol is, to some extent, in line with the findings by Mekonnen et al. (2018) and Wang et al. (2012).

On the other hand, energy consumption in sugarcane ethanol is extremely low compared to maize and cassava ethanol. This is primarily attributed to a higher ethanol yield per hectare and a relatively shorter process. Compared with other research, the present study reports a higher net energy balance. In most studies, particularly in developed countries, mechanization is higher, and in most cases, their system boundaries include indirect input-related energy consumption. For instance, Seabra et al. (2011) consider the energy consumed in producing the agricultural and industrial inputs, which are excluded in the current study due to data inadequacy. Moreover, energy use in feedstock production is comparatively lower in developing countries where farming is labor-intensive. Given the methodological and system boundary disparities, these findings should be interpreted according to the stated assumptions.

Energy usage goes hand in hand with GHG emissions. As observed, the processing stage for maize and cassava ethanol is carbon-intensive. These emissions are zero for sugarcane ethanol as the bagasse-based energy used is considered carbon neutral (Kiatkittipong et al., 2009). The high emissions from maize and cassava ethanol stem from the diesel boilers assumed, implying a huge potential for emission reduction if replaced by bagasse-fired boilers. The ethanol distribution component of the supply chain, on the other hand, has an insignificant impact. In contrast, sugarcane transportation generates high GHGs because of the bulkiness and a lower ethanol yield per metric ton (80 l/t) of cane relative to maize and cassava

[27] Starch has to be converted first into fermentable sugars.

Table 5
All sugarcane cultivated on forestland with carbon stock value of 151 t CO2eq/ha.

	Sugarcane	Gasoline
Without LUC emissions but with co-product credits	0.24	2.38
Immediate year LUC emissions	31.12	
Carbon sequestration	−0.85	
Foregone carbon sequestration	1.17	
Carbon credit from co-product (under LUC)	−1.25	
Immediate year total	30.43	
Final year value	2.76	

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

ethanol. It would, therefore, take more trips to deliver sugarcane for a given volume, but this can be lessened by promoting sugarcane zoning.[28]

The present study reveals fertilizer application and mechanization as potential emission hot spots in feedstock production, which is consistent with other research findings. For example, in their evaluation of the rapeseed biodiesel system in Spain, Fernández-Tirado et al. (2016) reported considerable environmental burdens from fertilization. The default simulations of the current study suggest significant fertilizer emissions for sugarcane than maize because of a higher fertilizer application rate and mechanization. However, from the scenario analyses, these emissions would be substantially high for maize at the current (low) productivity levels if all acreage was fertilized. It would imply more fertilizer and metric tons of GHGs emitted. Lower crop yields and agricultural inefficiency typify most African countries, making biofuels a threat to food production and a driver of land conversion. As Baumert et al. (2018) report, lower land-use efficiency is one of the limitations of Jatropha biodiesel in Burkina Faso. A lower crop yield also explains the level of GHGs from mechanization in maize and cassava production.

Grassland conversion and deforestation cause massive soil organic carbon losses into the atmosphere. However, all ethanol would break even relative to gasoline in the grassland scenario. On the contrary, LUC emissions from deforested land are quite high. From the findings, not even sugarcane ethanol with its emission benefits would quickly offset the high carbon from Uganda's tropical forest biomass.

Thurlow et al. (2016) assume conversion of grassland and forestland with carbon stock values of 12.9 t CO2/ha and 75.7 t CO2/ha, respectively, for Tanzania's sugarcane ethanol production. The carbon sequestration rate of sugarcane is 4.1 and 1.6 t CO2eq/ha under small and large-scale farming, respectively. In their analysis, a carbon-neutral level relative to gasoline under deforestation is reached between 15 and 27 years for large-scale and small-scale sugarcane farmers, respectively. They also report moderate GHGs from grassland conversion with a carbon-neutral level achieved in 2 to 3 years. Schuenemann et al. (2017) adopt a similar carbon stock value for grassland as Thurlow et al. but a sugarcane carbon sequestration rate of 1.22 C/ha (4.47 t CO2/ha). They find that a liter of sugarcane ethanol would emit between 1.82 and 1.52 kg CO2 in 10 years under land expansion, while this range drops to 1.37 and 0.91 kg CO2/L for a constrained land supply.

In comparison with Scheunemann et al. and Thurlow et al., the current study adopted higher carbon stock values. To a larger extent, this disparity is explained by the differences in soils and climatic conditions. Nevertheless, Scheunemann et al., Thurlow et al., and the current study demonstrate the risks of LUC and its implications. A vast literature already emphasizes the consequences of LUC emissions (Fargione et al., 2008; Searchinger et al., 2008). For example, Machado et al. (2020) found that land-use, land-use change, and forestry emissions dampened the emission reduction benefits in the energy sector. This emphasizes the need to promote low-carbon energy. If coupled with improved crop productivity, it

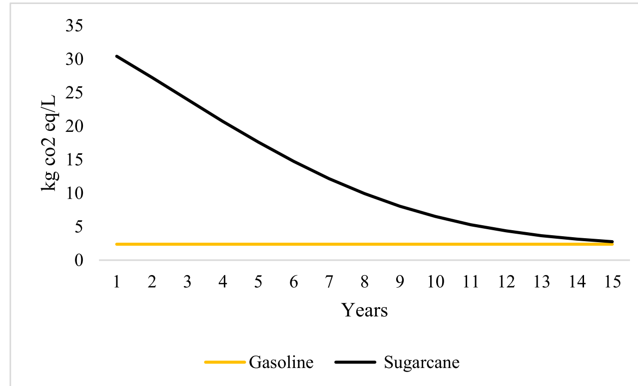


Fig. 4. Emissions per liter of sugarcane ethanol and gasoline (All sugarcane on 151 t CO2eq/ha forestland).

would maximize ethanol (biofuel) benefits for the low-income agriculture-dependent economies, given their agricultural comparative advantage. This point is accentuated in the detailed analysis of Ghana's biofuel target and input requirements by Iddrisu and Bhattacharyya (2015). While the reduction in national emissions is marginal, the present study demonstrates the emissions-reducing potential of ethanol in Uganda and similar agriculture-dependent economies. It also shows how poor crop yields require urgent attention. Therefore, agricultural support such as investment in electricity, water, and irrigation infrastructure would reduce crop risks originating from unreliable rainfall, enhancing productivity and moderating fertilizer needs. Additionally, cleaner biomass-based energy projects should be encouraged.

The water footprint portrays crop and ethanol yields, precipitation, and the crop growth period as crucial factors in determining the total water requirements. For instance, cassava has the highest per liter water consumption but zero irrigation requirements. This stems from its one-year growth period, over which there are about six months (March to May and September to November) of heavy rainfall. Similar factors and disparities in methodologies explain the variations in water requirements across studies. For example, Mekonnen et al. (2018)[29] report water requirements of 992 L/L for the US corn ethanol and 1280 L/L for Brazil's sugarcane ethanol, while the values in Scheunemann et al. range between 1720 L/L to 3387 L/L for Malawian sugarcane ethanol.

Regarding land, an addition of about 1.36% of the total agricultural land in 2017 would be required. This demand for land is minimal. Moreover, adopting sugarcane and cassava as feedstocks and improving crop yields may diminish it.

Table C.1 in SM Appendix C summarizes additional findings from studies outside Africa. Despite the significant differences, the analyses portray hotspots and possible emission ranges, which permit meaningful and consistent comparisons.

Conclusion and policy implications

This research applies a recursive dynamic CGE model to assess the land, energy, water, and carbon footprints of maize, cassava, and sugarcane ethanol in a natural resource-dependent economy. All three pathways have positive energy balances and lower carbon footprints in the absence of land-use change. However, grassland conversion and deforestation would cause massive soil organic carbon losses into the atmosphere. Nonetheless, all ethanol would break even relative to gasoline in the grassland scenario, and national emissions would fall. On the contrary, LUC emissions from deforested land are quite high.

[28] In this context, sugarcane zoning relates to a situation where more than one sugar mill/ethanol processor cannot be established within the same area and outgrowers in that area cannot supply sugarcane ethanol outside that area.

[29] Mekonnen et al. (2018) adopted yields from the FAOSTAT online database which were about 11 and 75 mt/ha for corn and sugarcane, respectively. These are considerably higher than the 2.2 for maize (corn) and 60 mt/ha for sugarcane in Uganda. Additionally, the corn ethanol yield in the current study is 370 L/mt compared to 425 l/mt in Mekonnen et al.

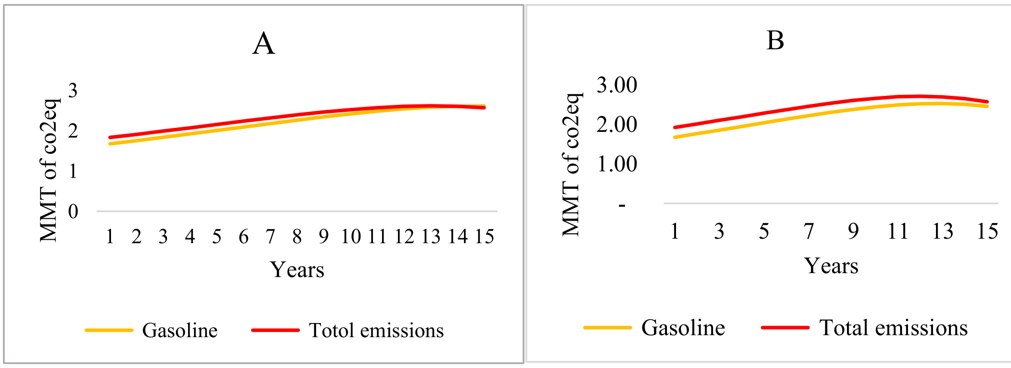


Fig. 5. Plot of total and gasoline emissions in million metric tons (MMT) of carbon dioxide equivalent.

Table 6
Water footprint in liters per liter of ethanol (L/L).

	Maize	Cassava	Sugarcane
Before co-product allocation			
Green water	5170.77	6350.10	4077.42
Blue water	11.10	11.10	14.30
Total water	5181.87	6361.20	4091.72
After co-product allocation			
Green water	4653.70	5715.09	3425.03
Blue water	9.99	10.00	12.01
Total water	4663.69	5725.09	3437.04

The study also reveals ethanol processing and feedstock farming as potential emission hotspots, particularly for the maize and cassava ethanol pathways. Overall, sugarcane ethanol is superior to maize and cassava ethanol. Its emissions savings are primarily attributed to the zero process emissions, carbon sequestration, and the negative emissions accredited to the surplus electricity. Despite this, its emission benefits would less than offset the high emissions from deforested land. While the reduction in national emissions is marginal, there are higher prospects of significant reductions with the promotion of low-carbon energy technologies. The additional land requirements are minimal. Moreover, adopting sugarcane and cassava as feedstocks and improving the crop yield may diminish this demand. Therefore, agricultural support such as investment in electricity, water, and irrigation infrastructure would reduce crop risks originating from unreliable rainfall, enhancing productivity and reducing land and fertilizer needs. Additionally, cleaner biomass-based energy projects should be encouraged.

A few limitations were encountered in this study due to methodological and data constraints. First, modeling national emissions using an emission intensity does not account for the dynamics in carbon efficiency. Second, the linear allocation of LUC emissions only shows the breakeven point relative to gasoline. However, this can be extended to applying a discount factor and ethanol production time horizon to account for variations in GHGS. Third, only direct LUC emissions are considered; expanding the system boundary to indirect and other excluded direct inputs would provide additional insight. Fourth, the employed crop model estimates approximate water use, which does not

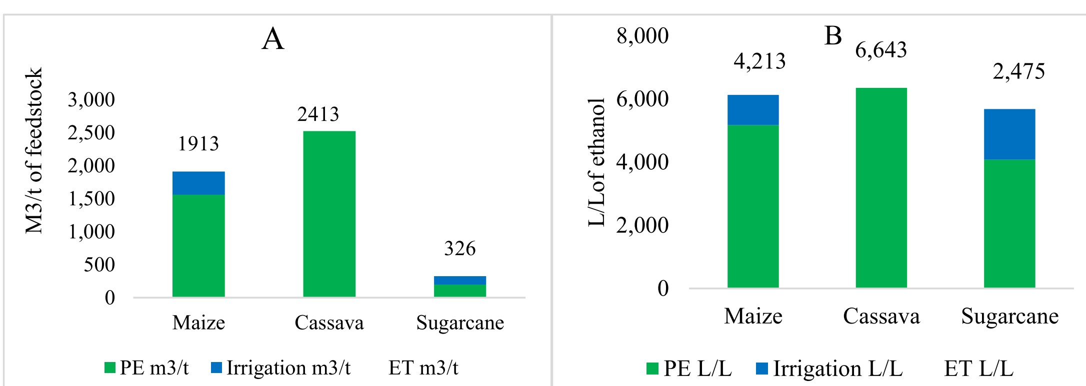


Fig. 6. Water footprint in cubic meters (m^3) per metric ton (t) and liters of water per liter of ethanol (L/L) before allocation to co-products.
ET refers to evapotranspiration and PE precipitation (green water). Irrigation accounts for the blue water in agriculture. ET m^3/t and irrigation m^3/t divides ET m^3/ha and Irrigation m^3/ha, respectively, by the yield t/ha.

Table 7
Water footprint and irrigation water requirement before allocation to co-products.

Feedstock	ET m^3/ha	PE m^3/ha	Irrigation m^3/ha	Irrigation m^3/t	Yield t/ha	Ethanol yield L/t	ET L/L	PE L/L	Irrigation L/L
Maize	4209	3429	780	354	2.2	370	5171	4213	958
Cassava	7722	8078	–	–	3.2	380	6350	6643	–
Sugarcane	19,572	11,880	7692	128	60	80	4077	2475	1602

ET refers to evapotranspiration, PE precipitation, ha hectare, and m^3 cubic meters of water. ET L/L and PE L/L are derived by converting ET and PE in m^3/ha to liters per ha by multiplying with a factor of 10. This value is then divided by the product of the ethanol yield L/t and the feedstock yield in t/ha. Irrigation L/L is the difference between the ET L/L and PE L/L.
Note that, despite sugarcane ethanol having the lowest irrigation requirement per metric ton, it has the highest per liter need because of a lower ethanol yield.

Table 8
Results from the parametric and scenario analyses.

	A	B Processing +50%	C Processing −50%	D Yield +50%	E Co-product share at 0.39	F Fertilizer 100%
Maize	2.34	2.71	1.97	1.87	–	3.12
Cassava	1.82	2.19	1.44	1.48	–	–
Sugarcane	0.45	–	–	0.33	0.29	0.49

In column A are results from scenario 2 with LUC emissions from grassland with 26 t CO2eq/ha. In column B, processing emissions are increased by 50%, column C a reduction of the same percentage, in D, the yield of all feedstocks are increased by 50%, in E energy-based approach is applied to allocated emissions between sugarcane ethanol and bagasse electricity. Lastly, F records an impact from fertilizing all maize and sugarcane acreage.

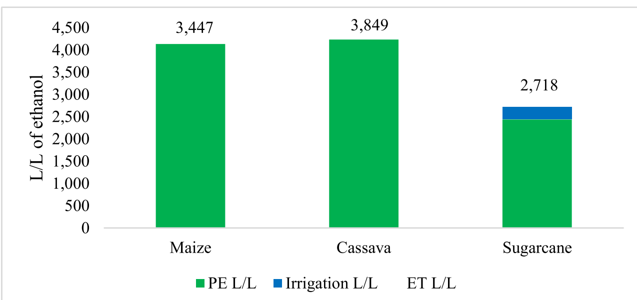


Fig. 7. Water footprint in liters of water per liter of ethanol (L/L).
ET refers to evapotranspiration and PE precipitation (green water). Irrigation accounts for the blue water in agriculture.

take into account variations in weather conditions. This research can therefore be extended to a model that captures uncertainty in crop yields. Further research on possible water pollution, biodiversity loss, and societal equity would also contribute to developing sound and more effective biofuel policies.

Declaration of competing interest

I declare no conflict of interest.

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Appendices. Supplementary data

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Paper IV

Poverty and inequality implications of biofuels in poor agriculture-dependent economies

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Abstract

This study uses a recursive dynamic CGE and a microsimulation model to examine the potential impact of ethanol production on poverty and income distribution in poor agriculture-dependent economies. Using the case study of Uganda, the findings show high potential for enhanced household income and no significant impact on income inequality. However, the concomitant increase in commodity prices surpasses the growth in household incomes, resulting in rising poverty. While the increase in poverty is modest, it reflects an imminent danger from increasing food prices. Enhancing feedstock yields dampens commodity prices and lowers poverty. Hence, despite their comparative advantages in agriculture, developing countries may fail to realize the full benefits of biofuels at the current agricultural productivity levels. Therefore, biofuel policies should be jointly pursued with improved agricultural productivity and efficiency in order to expand and sustain the biofuel industry. Lastly, it is mostly the rural unskilled labor wage that rises most, but the overall findings show no significant changes in the income distribution.

Keywords: Biofuels, Poverty, Inequality, CGE, Microsimulation.

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1.0 Introduction

Agriculture is the predominant source of livelihood for the largest share of the population in most developing countries. This places biofuel programs at the forefront of these countries' development agendas. Biofuel's potential to reduce poverty is premised on the demand and market expansion for crops and the growth in factor employment. From basic economic theory, increased demand for a commodity raises its price. Similarly, the demand for biofuel feedstocks may cause food prices to rise. The price relationship between biofuels and crops is precisely presented and empirically examined in various papers considering biofuels conversion yields (De Gorter & Just, 2008; Drabik, 2011; De Gorter, Drabik, & Just (2013). These papers invariably confirm a positive price relation, which may further be reshaped by existing biofuel policies (Drabik, Ciaian& Pokrivčák, 2016).

Rising crop/food prices and increased activity in farming can enhance agricultural income. An important empirical question is whether this income growth and increasing food prices translate into reduced poverty. For example, the 2007/2008 and 2010/2011 upsurges in prices of commodities, including food, were to some degree attributed to increased biofuel production (Malins, 2017). There were fears that biofuels would have implications for food security and poverty levels, particularly for the poor net food buyers (FAO, 2008). However, some scholars contend that higher food prices are not necessarily detrimental but can lead to declining poverty levels (Van Campenhout et al., 2018). Similar findings have also been suggested regarding biofuel production (Arndt et al., 2010); Arndt et al., 2012; Boccanfuso et al., 2018). It is, however, essential to note that factors such as feedstock types may have a considerable influence on the outcome. The impact will, in part, depend on how quickly agricultural supply and wages respond to price changes (Headey, 2018). Furthermore, the share of the feedstock crops in the consumption basket, as well as the individual and household characteristics, also determine the magnitude of the price impact. Additionally, where food production and traditional exports decline due to competition for resources, it raises another question whether the economic benefits of biofuels surpass these risks, particularly in countries with considerable numbers of poor food consumers.

Moreover, second-round effects, such as exporting or substituting biofuels for imported petroleum fuels, can induce an appreciation of the local currency (Arndt et al., 2010), causing further distributive and poverty implications.

This uncertainty forms the basis for the research questions of this study, which I address using the case study of Uganda. The following questions are, therefore, pertinent. Will increasing crop prices and income growth reduce poverty in Uganda and similar developing countries? What are the likely implications of ethanol production and resource reallocation for the distribution of income? What would be the appropriate recommendations given the outcomes regarding the above question?

Uganda presents a good case study, given that almost two-thirds of its working population is engaged in agriculture (Uganda Bureau of Statistics ((UBOS), 2018). Despite this significance, the sector contributes only 24 percent to total GDP. In addition, rural poverty headcount is about 23 percent, while national and urban rates are approximately 20 and 12 percent, respectively. Income inequality is 42 percent. Food and non-alcoholic beverages expenditure is over 40 percent of the consumption budget for a typical Ugandan household. This share is around 49 percent for rural and 43 for urban households, having changed marginally from the 2016/17 respective values of 51 and 38 percent (UBOS, 2021).

To address the objectives of this study, I use a recursive dynamic computable general equilibrium (CGE) and a microsimulation model. I calibrate the CGE model to the 2016/17 Uganda social accounting matrix (SAM) with ethanol derived from maize, cassava, and sugarcane. The last two feedstocks are already suggested by the Ministry of Energy and Mineral Development (MEMD) (MEMD, 2020), while maize is also currently used to produce potable ethanol. I then simulate approximately 0.19 billion liters adequate for a 10 percent blending, which I find feasible for an infant industry. Finally, I feed the macro results from the CGE to the microsimulation model for a distributive analysis.

There is a growing literature investigating the impacts of biofuels on poverty in relatable countries. For example, Arndt et al. (2010) examined large-scale sugarcane ethanol and Jatropha biodiesel production in Mozambique. They found a decline in the poverty incidence, despite a fall in traditional exports due to exchange rate appreciation. Similarly, Arndt et al. (2012) reported poverty reductions for the various sugarcane and cassava scenario ones. Schuenemann et al. (2017) also found that sugarcane ethanol leads to a decline in poverty levels for Malawi, assuming land expansion. The investigation by Debela and Tamiru (2016) shows lower poverty rates from investing in sugarcane ethanol and Jatropha, castor bean, and palm oil biodiesel in Ethiopia. Similar outcomes have been observed for sugarcane ethanol in Tanzania by Thurlow et al. (2016). Boccanfuso et al. (2013) assessed the macroeconomic and distributional impacts of Jatropha biodiesel in Mali. GDP grew slightly only when idle land was utilized, while rural poverty declined under all scenarios, including crop displacement.

This study fits in the above literature on biofuels and contributes to the debate on biofuels versus food security and poverty by highlighting important implications. The main point of departure from the existing literature is the evaluation of an ethanol volume for domestic use, which I consider less ambitious in the short to medium term. This is relevant considering the trade barriers developing countries face and the sustainability standards that may be restrictive in the current state. The key strength of this study is the evaluation of the impact of ethanol on poverty and the use of the Shapley method to decompose it by input variables to the micro model. This is important in identifying the role of each variable in the evolution of poverty estimates and offers a clue to decision-makers on what to focus on.

The rest of the paper is organized as follows: The next section presents the data, methods, and simulations. Section three presents the descriptive statics, while four reports and discusses the results. Finally, the paper concludes and provides policy implications in Section five.

2.0 Data and Methods

The primary datasets in this study are the 2016/17 Uganda social accounting matrix (SAM) developed by Tran et al. (2019) and the Uganda National Household Survey (UNHS) data of 2016/17. The SAM was obtained from the Ministry of Finance, Planning and Economic Development, while UNHS data is from the Uganda Bureau of Statistics (UBOS). Data on gasoline imports and consumption volume are from the Ministry of Energy and Mineral Development and UBOS, and ethanol prices were obtained from ethanol processors. Lastly, elasticity parameters are from the literature and the technical coefficients from Zhou and Kojima (2011). These are adopted as applied in Nakamya (2022) [24].

The study applies a dynamic CGE (macro model) calibrated to the SAM and a microsimulation (micro) model based on the UNHS survey data. The two models are linked using a microsimulation toolkit developed by Tiberti et al. (2017). This is implemented in STATA, using the Distributive Analysis Stata Package (DASP) by Araar and Duclos (2013). The CGE model is based on a representative household assumption and can only estimate variable changes at the sectoral and macro levels. On the other hand, the microsimulation model is built from data on individuals and households. Linking the two models enables examining the macroeconomic effects of a policy while taking into account the distributional effects and individual heterogeneity.

2.1 The Macro model

The macro model is relatively similar in structure to that in Nakamya (2022). It is an adaptation of the PEP-1-t single-country, recursive dynamic CGE model by Decaluwé et al. (2013). The model contains 39 activities and commodities. A Leontief production function combines the aggregate value-added and aggregate intermediate inputs at the top level. At the lower level, individual intermediate inputs of the

[24] This data is available in the supplementary data file at https://doi.org/10.1016/j.esd.2021.12.012

aggregate intermediate are governed by the same function, except for the Ethanol-blending sector, which applies a constant elasticity of substitution (CES) function. Aggregate capital and the labor composite are combined in a CES framework, and the same function is applied to the labor types and aggregate capital components.

Domestic production assumes imperfect substitutability between domestic sales and exports; hence, these are allocated in a constant elasticity of transformation (CET) function. On the other hand, total domestic consumption also assumes imperfect substitutability between domestic production and imports, represented by the CES function. Domestic consumption (total absorption) comprises household consumption, public demand, investment demand, intermediate demand, and the demand for margin services. The model assumes exogenous prices for both exports and imports. Nonetheless, exporters can increase their market shares depending on the elasticity of demand and the level of world prices relative to the free-on-board price.

There are eight households categorized as rural and urban across four income quartiles. These are, however, aggregated to only rural and urban when mapping to the survey data. Households earn income from factor endowment and transfers and spend on consumption, taxes, savings, and transfers. 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 [25]. 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 based on the initial shares in total capital income and sectoral profitability. After allocation, the capital becomes immobile, earning sector-specific rental rates.

Total investment is a function of foreign borrowings and savings from households, firms, and the government. The savings-investment balance is savings-driven, and investment is endogenous. Aggregate investment consists of changes in stocks and gross fixed capital formation, and the latter combines private and public investment expenditure. While some recommend the consumer price index as a good model numeraire, I instead apply the nominal exchange rate with the real exchange rate as a clearing variable of the current account. This choice was based on the argument by de Janvry and Sadoulet (2002) [26] regarding choosing a more neutral model numeraire. Government income is a sum of non-tax income

[25] Land mobility in this case implies usage across alternative activities.
[26] If the model numeraire is made up prices that are relatively falling, the relative price change would be interpreted as an increase in prices causing high negative indirect effects.

from the rest of the world, revenues from taxes on products and production activity, as well as household and firm income taxes. Its savings are a flexible residual between revenues and expenditure, which are fixed, and all the tax rates are exogenous.

2.2 The microsimulation model

The microsimulation (MS) model is built from the UNHS dataset containing 15,672 successfully interviewed households from all the districts of Uganda. It includes data on personal details and variables such as education level, household consumption expenditure, and household income, among others. The estimated population at the time was 37.7 million people, with 76 and 24 percent living in rural and urban areas, respectively.

The model is behavioral, comprising income-generating and household consumption modules. The income-generating module estimates income from labor, land, capital, and other exogenous sources like transfers. First, labor supply in the various occupation alternatives is determined, and earnings from each source are calculated.

2.2.1 Modeling labor supply

Labor supply is modeled as a discrete choice using a multinomial logit model, arising from utility maximization. Individuals choose among wage work, non-agriculture self-employment, farming, and not employed. The choice model is set up such that the utility associated with each alternative is a function of individual and household characteristics as specified in Equation 1.

$$U_{ij} = V_{ij} + \varepsilon_{ij} \qquad (1)$$

where j are the occupation alternatives, including wage work, non-agriculture self-employment, farming, and not employed, as the base case. U_{ij} refers to the utility for individual i from alternative j, and V_{ij} is the utility component determined by the observable characteristics. The observable characteristics include household region, area of residence (rural or urban), household head or not, number of children in the household, gender of a household member, age, education level, and marital status. ε_{ij} denotes the unobserved random component.

Estimating income

Once choices are determined from the occupation choice model above, household income is estimated accordingly: income from individual wages, non-wage income for the self-employed in non-agriculture, and income from farming.

Wage income

Wage income is estimated using a selection model and a mincer equation by applying the Heckman procedure with exclusion restrictions. The selection equation is a probit model where the observed binary outcome variable Y relates to a continuous unobservable dependent variable y_i^* in a classical linear regression model as specified in Equation 2.

$$y_i^* = X_i'\beta + u_i \qquad u \sim N[0, \delta^2] \tag{2}$$

$Y_i = 1$ if $y_i^* > 0$ and an individual is a wage worker, while $Y_i = 0$ if $y_i^* \leq 0$ and the individual is not in employment. β are the coefficients of the covariates X_i', which include marital status, age, gender, region, and the number of children. u_i is a standard normally distributed error term with a zero mean and constant variance ($N[0, \delta^2]$).

The wage model in Equation 3 is a mincer equation used to estimate wage income as a function of gender, household head or not, region, age, age squared, and education level. This equation excludes marital status and the number of children in the selection equation. I imposed the exclusion restriction for more robust identification after comparing the models with and without exclusion restrictions. And the two variables excluded had a significant impact in the selection equation as required.

$$ln\, wage_i = X_i'\beta + u_i \tag{3}$$

$\ln wage_i$ is the log of the wage for individual i, X_i' a vector of covariates listed above, β a vector of coefficients, and u_i is the error term assumed to be normally distributed with a zero mean and constant variance.

Estimating profit or non-wage income

Non-wage income for farmers and the non-agriculture self-employed is estimated at the household level using a profit function specified as a Cobb-Douglas production function.

$$ln\, \pi Y_h^j = \beta_0 + \beta_1 lnsk_h^j + \beta_2 \ln usk_h^j + \beta_3 lnX_h + u_h \tag{4}$$

$ln\, \pi Y_h^j$ is total non-wage income from sector *j* (j is an index for agriculture or non-agriculture) for household *h* as a function of the number of skilled family workers $lnsk_h^j$, the number of unskilled family workers $\ln usk_h^j$, other household characteristics lnX_h, and the unobservables u_h. Other household characteristics include household size, the average age of the household member, urban or rural residence, region, gender of household head, and education level of a household head. An endogenous test [27] is performed on the variables, and it reveals that the variable "number of working family members" is endogenous. Therefore, the estimation follows an instrumental variable approach. The variables "household size" and "average age of household member" are used as instrumental variables for the "number of working family members."

Household profit income is divided by the number of household working members (in the farm or household enterprise) to obtain individual profits. Since wage income is also estimated at an individual level, total household income is derived by summing the earnings of family working members by source plus any exogenous income, as depicted in Equation 5.

$$YH_h = \sum_{i=1}^{n,sk} yw_{i,h} + \sum_{i=1}^{n,usk} yw_{i,h} + \sum_{i=1}^{n,sk,unsk} yag_{i,h} + \sum_{i=1}^{n,sk,unsk} ynag_{i,h} + yoth_h \quad (5)$$

Therefore, YH_h is income for household h as a total of wage income $(yw_{i,h})$ for the skilled (sk) and unskilled (usk), income from agriculture $\left(yag_{i,h}\right)$ and non-agriculture self-employment $\left(ynag_{i,h}\right)$, summed over working household members n, plus any exogenous income like transfers $(yoth_h)$.

2.2.2 The household consumption module

The household consumption module is based on household income, consumption commodities, and commodity prices. For each period t, the MS model predicts the changes in wages and profit income. Changes in real household consumption are derived from variations in household income and consumer prices, and these are used to estimate variations in poverty and income distribution. The approach applies a household-specific price index which captures the heterogeneity of the effect of the price change among households. This is achieved by defining equivalent income derived from an indirect utility function and expressed as an expenditure function in Equation 6.

$$eh_{h,c}^t = eh_{h,c}^t(p^0, p_c^t, x_{h,c}^t) \quad (6)$$

$eh_{h,c}^t$ is the equivalent income of household h living in cluster c expressed as an expenditure function with p^0 the vector of base year prices, p_c^t is consumption prices in period t, and $x_{h,c}^t$ the consumption by household h in period t.

I use the Foster, Greer, and Thorbecke (FGT) class of poverty measures (Foster, Greer & Thorbecke, 1984) to estimate the poverty and Gini indices across rural and urban households and the entire

[27] A postestimation endogenous test which implements the Durbin-Wu-Hausman test was invoked.

population. The welfare index is the per capita expenditure, and the measures are depicted in equation (7) below.

$$P_a^t(Z) = \frac{1}{N}\sum_{h=1}^{H} wgt_{h,c} \, . \, n_{h,c}\left[\frac{z \, - \, eh_{h,c}^t\left(p^0, p_c^t, y_{h,c}^t\right)}{z}\right]^{\alpha} \quad ; \quad a = 0,1,2 \qquad (7)$$

Where z is the monthly poverty line, N the total number of households in the survey, and α is the poverty aversion parameter. The total number of households is also equal to the product of the sampling weight $wgt_{h,c}$ and household size $n_{h,c}$ of household h in cluster c. The study focuses on the headcount ($a = 0$) and the poverty gap ($a = 1$). See Tiberti et al. (2017a, 2017b) for a detailed exposition of the approach.

2.3 Scenarios

There are three scenarios: The reference and ethanol scenarios with and without improved feedstock productivity.

Reference scenario

The reference scenario provides a basis to compare with the ethanol scenarios. The CGE reference scenario assumes annual population and total factor productivity growth rates of 3.2 and 2.2 percent, respectively. The growth rate for all skilled and urban unskilled labor is 4 percent, while unskilled rural labor grows at 2.2 percent. The growth rate for skilled labor reflects the steady improvement of education attainment (Wiebelt et al., 2018) alongside stagnant employment levels. For all unskilled labor, the rates signify unemployment and the apparent rural-urban migration. Consequently, real GDP is projected at about 4.0 percent annually. The model is run from 2016 to 2031, when ethanol production is held at virtually zero in the reference simulation. Changes in the variables of interest are then calculated as cumulative percentage changes from their base year (2016) values.

Scenario one Scenario one is the ethanol scenario that simulates ethanol, assuming the current feedstock yields. This is intended to examine the impact while maintaining the status quo. Since MEMD already identified cassava and sugarcane as potential feedstocks, yet maize is also used to produce portable ethanol, I restrict each to an equal share in the total ethanol production.In scenario one, the stock of capital is gradually increased as feedstock and ethanol producers draw in more factors of production. According to historical trends, gasoline consumption will be around 1.94 billion liters by 2031; hence, 0.194 [28] billion liters of ethanol will be required (Nakamya, 2022). The model is rerun for the same period, 2016-2031, but with a gradual increase in capital until 0.194 billion liters are produced in the final period. This is implemented by arbitrarily adjusting the taxes on ethanol to equate its price to that of gasoline. These assumptions, particularly the exogenous increase in capital, imply implicit government support for investors and mandatory consumption. Similarly, cumulative percentage changes in the variables of interest are calculated as changes from their base year (2016) values [29].

Scenario two

Scenario two assumes increased feedstock productivity (henceforth, scenario two). Comparing the results from the two ethanol scenarios allows for recommendations regarding the applicable best practices. The productivity of all three feedstocks grows at 4.3 percent annually. This is an arbitrary decision based on the current yields and what may be feasible in the medium term.

2.4 Linking the CGE with the MS model

The SAM and UNHS data are reconciled regarding labor categories, income sources, and consumption commodities. I aggregated all the commodities into twelve categories as presented in Table B.3, and labor into skilled and unskilled for rural and urban in Table B.4 of Appendix B. Income sources include wages, profits from non-agricultural self-employment, and farming. The Uganda SAM does not distinguish between wage earners, the self-employed in non-agriculture, or farmers. In this respect, wage earners and non-agriculture self-employed from the survey data are approximated by urban workers and farmers by rural workers in the SAM.

As earlier mentioned, macroeconomic changes in employment levels, wages, incomes for the self-employed in non-agriculture, incomes of farmers, and commodity prices from the CGE and transmitted to the MS model. Note that both the reference and ethanol scenarios results from the CGE are simultaneously fed into the MS model, which estimates poverty and income distribution under each. Precisely, the MS estimates variations in poverty and income inequality with respect to the base year values (2016 values) for both the reference and ethanol simulations. It is worth noting that the estimated indices in each period vary with respect to the previous year's values for both the reference and ethanol simulation scenarios, generating a corresponding trajectory for each. In each scenario, poverty declines along the trajectory if the FGT index in the current period is smaller than in the previous. Furthermore,

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

[29] Recall that the baseyear 2016 is the same under the reference and simulation scenarios.

the difference between the two trajectories at each period t determines the impact of a given policy or exogenous shock. In other words, the variations of the FGT indices and GINI coefficients of the ethanol scenario from those of the reference scenario determine the impact of ethanol production on poverty and income distribution. Any simulated policy is poverty-reducing if the trajectory of the simulation scenario lies below the reference trajectory; otherwise, it is rising

3.0 Descriptive statistics

Consistent with the UNHS (2016/17) report, rural has the highest number of farmers and the self-employed in non-agriculture than urban. The distribution of wage workers across rural and urban areas shows relatively equal shares; nonetheless, urban areas have more wage workers (see Tables 1). Specifically, 49.59% of the wage workers reside in rural areas, but these are just 12.67% of the rural working population in contrast to the 35.81 percent for urban. This is because the urban population is small compared to rural. The Central region has the highest number of wage workers and the self-employed while the Eastern and Northern regions dominate farming (see Tables 2). However, within the regions themselves, agriculture is still a significant source of employment. For example, about 41 percent of the Central population are employed in farming.

Regarding poverty, Figure1 shows that the majority of the rural population is concentrated around the poverty line. The same phenomenon is observed for the Eastern and Northern regions (see Figure 2). A comprehensive description of the UNHS data can be found in the UNHS report (UBOS, 2018).

Table 1. Summary of occupation by residence

Occupation **A**	Rural **B**	**Rural C % share**	Urban D	**Urban E % share**	Total **F**
Wage worker	3,149.00	**12.67**	3,201	**35.81**	6,350
Row 1 (%)	*(49.59)*		*(50.41)*		*(100)*
Self-employed non-agriculture	3,319.00	**13.36**	2,583.00	**28.89**	5,902
Row 2 (%)	*(56.24)*		*(43.76)*		*(100)*
Farmers	18,379.00	**73.97**	3,156.00	**35.30**	21,535
Row 3 (%)	*(85.34)*		*(14.66)*		*(100)*
Total	24,847.00	**100**	8,940.00	**100**	33,787
Row 4 (%)	*(73.54)*		*(26.46)*		*(100)*

Note: Columns B and D represent the area of residence, and the bold columns C and E are the corresponding percentage share of each occupation in that particular residential category. The last column, F, is the total number of respondents in that occupation category. The rows show the number of workers in that particular occupation category and the corresponding percentage share in the area of residence in parentheses.

Table 2. Summary of occupation by region

Occupation **A**	Central **B**	**Central** **C**	Eastern **D**	**Eastern** **E**	Northern **F**	**Northern** **G**	Western **H**	**Western** **J**	Total **K**
Wage worker	2,135	**31.25**	1,303	**12.24**	1,136	**13.34**	1,776	**22.79**	6,350
Row 1 (%)	*(33.62)*		*(20.52)*		*(17.89)*		*(27.97)*		*(100)*
Self-employed non-agriculture	1,882	**27.55**	1,273	**11.96**	1,443	**16.95**	1,304	**16.73**	5,902
Row 2 (%)	*(31.89)*		*(21.57)*		*(24.45)*		*(22.09)*		*(100)*
Farmers	2,815	**41.20**	8,072	**75.81**	5,934	**69.71**	4,714	**60.48**	21,535
Row 3 (%)	*(13.07)*		*(37.48)*		*(27.56)*		*(21.89)*		*(100)*
Total	6,832	**100**	10,648	**100**	8,513	**100**	7,794	**100**	33,787
Row 4 (%)	*(20.22)*		*(31.52)*		*(25.20)*		*(23.07)*		*(100)*

Similar to Table 1. The columns represent the region and the corresponding percentage share of each occupation in that particular region. The last column, K, is the total number of respondents in a given occupation category across all regions. The rows show the number of workers in that particular occupation category and the corresponding percentage share in a given region in parentheses.

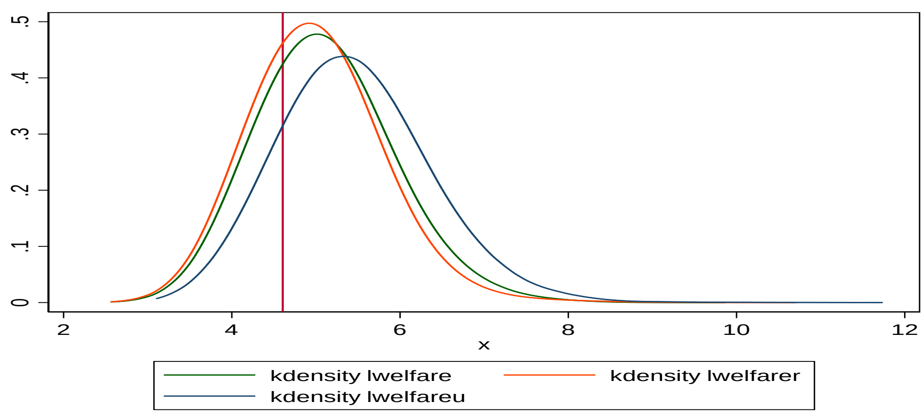


Figure 1: Kernel densities for the welfare variable (per capita expenditure) around the poverty line
Lwelfare, *lwelfarer*, and *lwelfareu* are welfare variables for Uganda as a whole, rural, and urban populations, respectively. The vertical line is the mean of the poverty line.

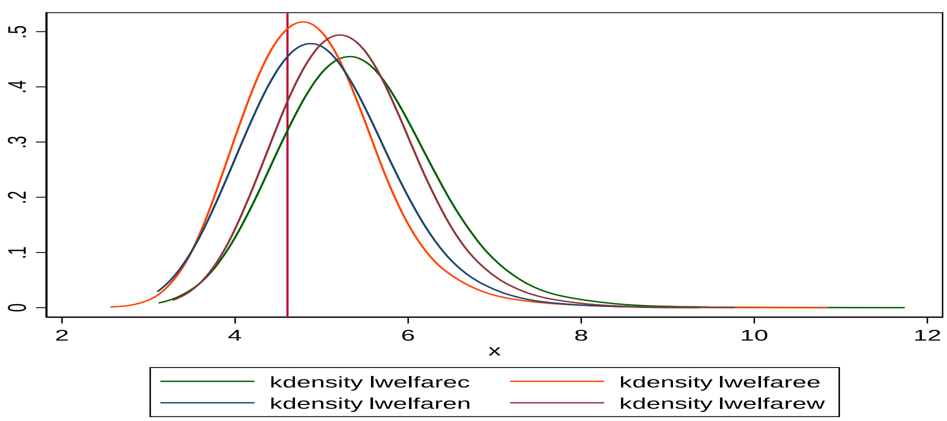


Figure 2: Kernel densities for the welfare variable (per capita expenditure) around the poverty line
Lwelfarec, *lwelfaree*, *lwelfaren*, and *lwelfarew* are welfare variables for Central, Eastern, Northern, and Western regions, respectively. The vertical line is the mean of the poverty line.

4.0 Results and discussion

This section presents and discusses the study findings. As expected, the magnitudes of the results are small because of a relatively smaller ethanol sector. Nonetheless, these findings are admissible and realistic for a medium-term analysis, as large ethanol volumes may not be feasible for an infant industry.

4.1 Selected sectoral and macroeconomic results

In Table 3 are the selected sectoral and macroeconomic impacts reported as percentage deviations from the reference scenario in the final year, 2031. According to the findings, ethanol production would expand the demand for feedstocks and the growth in its output. The feedstock sectors experience rising prices and revenues, drawing in more land and labor. This causes a corresponding increase in the sectoral-composite and economy-wide wages and land rents (see Table 4). Some activities, including the "Cash crops" and "Grain seeds" production, decline. Moreover, these are major exporting sectors whose output is further depressed by the appreciation of the exchange rate. The exchange rate appreciates due to a significant reduction in gasoline imports and the general movements in the trade balance. The decline in production and increased commodity prices raise the economy's average price level. Nevertheless, agricultural output and real GDP grow over the entire period, rising by 0.09 and 0.10 percent in the final year, respectively (See Table 3).

Table 3. Macroeconomic and sectoral impacts of ethanol

	Reference growth rate (%)	% deviation from the final year base value
Real GDP	4.0	0.10
Total agriculture	4.2	0.09
Cash crops	4.2	-0.98
Grain seeds	3.9	-0.28
Maize	4.1	1.26
Cassava	3.9	1.07
Sugarcane	4.4	10.54
Sugar manufacture	4.0	-1.09
Forestry	3.9	-0.01
Fishing	3.5	-0.04
Mining	3.3	-0.01
Other alcohol	3.6	-0.17
Food processing	3.5	-0.18
Other manufacture	3.6	-0.19
Trade	3.6	0.20
Consumer price index (CPI)	1	0.95
Real exchange rate	1	-0.94

A negative exchange rate value implies an appreciation of the local currency.

Wages and rents on capital and land grow (See Table 4). Although wage changes between periods are positive for all labor types, only unskilled rural labor exhibits positive cumulative changes (Table B.5 Appendix B). Nevertheless, the change in household income and real consumption is positive for all households, as reported in Table 5. Richer households gain more than poorer ones because the latter have higher capital endowments.

Table 4. Percentage change in factor prices

Sector	Land rent	Composite wage	Capital rental rate
Cash crops	1.47	0.91	-2.98
Grain seeds	1.47	0.95	-0.23
Maize	1.47	0.99	8.25
Cassava	1.47	0.93	6.92
Sugarcane	1.47	0.97	47.11

Notice: Because labor supply is fixed, changes in the economy-wide wage for each labor category are uniform across sectors, but the composite wage, which is a weighted average for all labor types, varies across sectors. Land rent is uniform across sectors because of the fixed supply. The large percentage change in the rental rate on capital in sugarcane is due to a small base value– the sugarcane sector is relatively smaller than other sectors.

Table 5. Percentage deviations in household disposable income and real consumption from the final base year value

	Disposable income	Real consumption
RuralQ1	1.04	0.09
RuralQ2	1.05	0.11
RuralQ3	1.05	0.10
RuralQ4	1.06	0.11
UrbanQ1	1.01	0.07
UrbanQ2	1.03	0.09
UrbanQ3	1.04	0.10
UrbanQ4	1.07	0.13

Q1 to Q4 correspond to the four income quartiles for both rural and urban households

4.2 Microsimulation results

In this section, I present and discuss the results from the microsimulation model. These results are subject to the limitation of a small ethanol sector, and this was evident from the start. Therefore, the magnitudes of the effects are small, making it difficult to perform some statistical tests. However, this was a deliberate decision to assume an ethanol volume that is likely to be feasible in the short to medium term. Besides, only domestic ethanol use is envisaged in Uganda's current biofuel programs [30]. Therefore, the

[30] The Biofuels General Regulations draft of 2020 is to guide the initial blending of 5 percent for ethanol and biodiesel. While a fuel blend of up to 20 percent was one of the MEMD Biomass Resource Management Investment Priorities for 2020/21, it has not been achieved. Most importantly, I chose a 10% blending level given the production constraints and vehicle compatibility issues.

aim is to evaluate the impact of production adequate for a 10 percent blending level. I also rely on other tests, as referred to in the discussion of the results.

4.2.1 The reference scenario

I run the CGE model forward for 15 years to generate a reference scenario. No ethanol is produced; however, the reference assumptions induce positive growth in real GDP, sectoral output, household income, population, factor supply, and total factor productivity. Essentially, all variables grow in each period. Commodity price deviations with respect to previous periods are positive but moderate. Nevertheless, the cumulative changes with respect to the base year values are negative for most commodities, owing to the invoked total factor productivity and projected economic growth. Cumulative percentage changes in the variables of interest are calculated and fed into the micro model to generate the MS reference scenario. The MS reference scenario depicts a year-on-year change in the poverty incidence, poverty gap, and inequality by the Gini coefficients. The national poverty headcount falls from 21 to 18 percent, while the poverty gap declines from 5 to 4 percent. The rural and urban poverty incidence drops from 25 to 22 and 12 to 8 percent, respectively. The Gini coefficient measuring income inequality rises from 0.44 to 0.48 at the national level, 0.39 to 0.42 for rural, and 0.54 to 0.53 for urban. Therefore, except for inequality, poverty declines continuously in the reference scenario [31].

4.2.2 Scenario one

As earlier mentioned in the methodology, ethanol production is increased gradually over a period of 15 years. Once again, cumulative percentage changes in the variables of interest passed to the MS model to generate a counterfactual scenario with poverty estimates in each period. Similar to the reference case, the poverty incidence and poverty gap decline for the entire simulation period. However, the trend of scenario one tends to deviate upward from the reference scenario. This reflects an increment in poverty relative to the reference case, and it is more pronounced for rural households. Figures 3, 4, and 5 plot the national, rural, and urban poverty trends. The poverty decomposition by income source and consumer prices in Figure 6 reveals that the entire negative effect is virtually attributed to the CPI, with a minor positive impact from wage changes. On the other hand, the effect of agricultural and non-agricultural non-wage income is insignificant.

[31] My reference poverty estimates slightly differ from the 21.4, 25, and 9.6 % for national, rural, and urban, respectively reported in the UNHS report (UBOS, 2018). There are also differences in the Gini coefficients. This is mainly due to the differences in the methodology and the macro model assumptions. For example, I deflate expenditure income using a deflator derived from the maximum value of the poverty line. Nonetheless, this should not affect the findings since the interest is to compare the ethanol simulation against the reference scenario.

In order to evaluate the poverty impact in absolute terms, I use population projections based on the current annual population growth rate of 3.2 percent. This translates to about 60 million people by 2031, which is consistent with Uganda's United Nations population projections for 2030 (UN DESA, 2015) [32]. Based on the population projections, the production of 0.19 billion liters of ethanol would push approximately 241,369 individuals into poverty, and about 82 percent of these would be in rural areas (Table 6). The poverty gap index also rises, as reported in the same table.

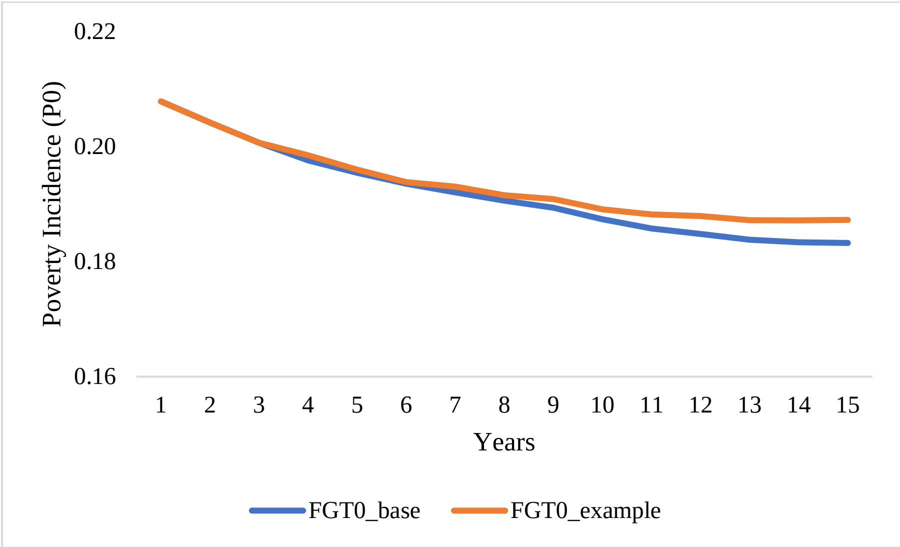
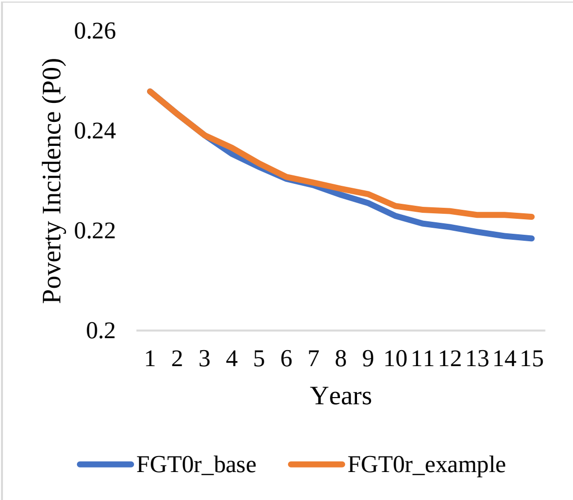
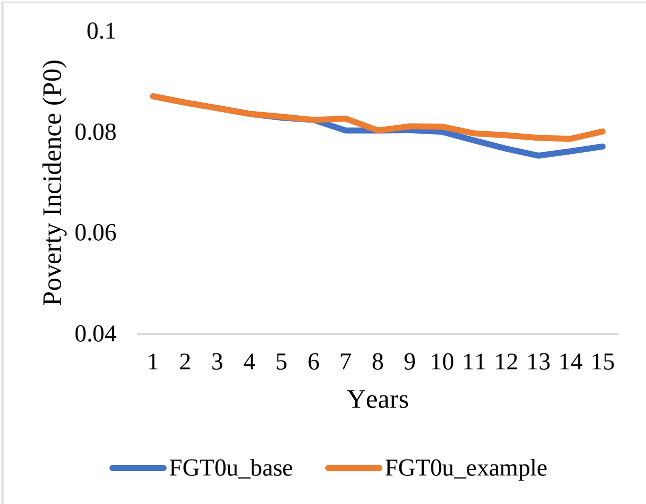


Figure 3. Population poverty incidence (P0) for the reference (FGT0_base) and scenario one (FGT0_sim)





[32] United Nations, Department of Economic and Social Affairs, Population Division (UN DESA) projects 61, 929,000 people for Uganda by 2030.

Figure 4. Rural poverty incidence (P0) **Figure 5. Urban poverty incidence (P0)**
FGT0r_base is the poverty incidence under the reference, while FGT0r_sim is for scenario one. Note that the scales in Figures 4 and 5 are similar to allow comparison.

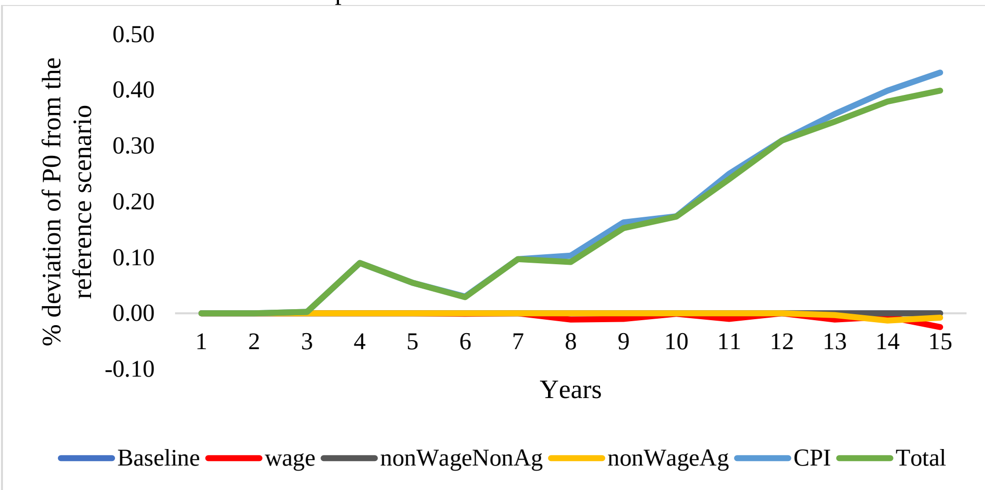


Figure 6. Scenario one- Poverty analysis decomposition by income source and the CPI

Table 6. Scenario one 2031 poverty effects due to ethanol production

		Uganda Reference	Uganda Ethanol sim	Rural Reference	Rural Ethanol sim	Urban Reference	Urban Ethanol sim
A	Population	37,713,658	37,713,658	28,500,000	28,500,000	9,213,658	9,213,658
B	P0 base year 2016/17	0.214	0.214	0.25	0.25	0.96	0.96
C	No. of poor	8,070,723	8,070,723	7,125,000	7,125,000	8,845,112	8,845,112
D	P0 Base year ref/eth sim	0.202	0.202	0.22	0.22	0.08	0.08
E	Population projections	60,491,467	60,491,467	45,729,624	45,729,624	14,761,843	14,761,843
F	P0 final year ref/eth sim	0.183	0.187	0.218	0.223	0.077	0.080
G	No. of new poor	11,083,241	11,324,610	9,989,431	10,187,590	1,138,823	1,182,472
H	No. of poor due to ethanol		241,369		198,159		43,648
J	Poverty gap index	0.045	0.046	0.054	0.055	0.017	0.018

Ref refers to the reference scenario, whereas sim is the ethanol simulation scenario.
Note: Row A records the base year official population levels and B the poverty estimates in the UNHS report. Row C is the number of poor based on the base year official values (rows A & B), not the reference scenario. Row D records poverty estimates in the base year of the reference scenario (these are similar to the base year estimates for the ethanol simulation because of zero ethanol). The projected population values in row E and end-of-period poverty estimates in F are used to calculate the number of new poor in row G under the reference and ethanol simulations. The last row, H, is the new poor attributed to ethanol production. These numbers are obtained as the difference between the values of the new poor under each scenario. Row J is the poverty gap index.

Scenario two (with increased productivity for maize, cassava, and sugarcane)

The SAM data shows that maize, cassava, and sugarcane yields are 2.2, 3.2 [33], and 60 metric tons per hectare (mt/ha). I increased the total factor productivity parameter for each feedstock by 4.3% in each period for the 15 years. This lowers the prices of commodities, including food—the prices for maize, cassava, and sugarcane decline between periods and cumulatively. In Figures 9, 10, and 11, the ethanol

[33] This is the yield for dried cassava chip, not fresh roots.

simulation dominates the reference for most of the period, except in the last three years. Furthermore, the positive impact of the wage on poverty slightly improves. This shows how increasing crop yields may depress the inflationary effects of ethanol production, leading to lower poverty levels. Similar to scenario one without enhanced productivity, the decomposition shows both the wage and CPI as the variables responsible for the decline in poverty (Figure 10). Agricultural and non-agricultural non-wage incomes remain insignificant.

Please note the following:

First, the benefits from increased productivity dissipate in the 12th year. This occurrence is consistent, emanating from the CPI and not the income variables (see Figure 10). I find this surprising, and it requires more investigation. Nonetheless, this should not undermine the validity of the findings.

Second, the contrast between the rural and urban poverty trends with respect to the reference scenario is fuzzy. I attribute this to the current occupational distribution between the two residential categories. For example, in Table 1, while only 15 percent (row 3 column D) of the farmers reside in urban areas, a significant number (35 percent, row 3 column E) of the urban population derives its livelihood from farming. At the same time, many rural households are net food buyers. These characteristics are likely to blur the distinction between the impacts on the two types of households. However, poverty changes are slightly more evident for the Eastern and Northern regions because many have their incomes close to the poverty line. On the other hand, the central and western regions exhibit minor variations (see Tables C.1 and C.2 of Appendix C).

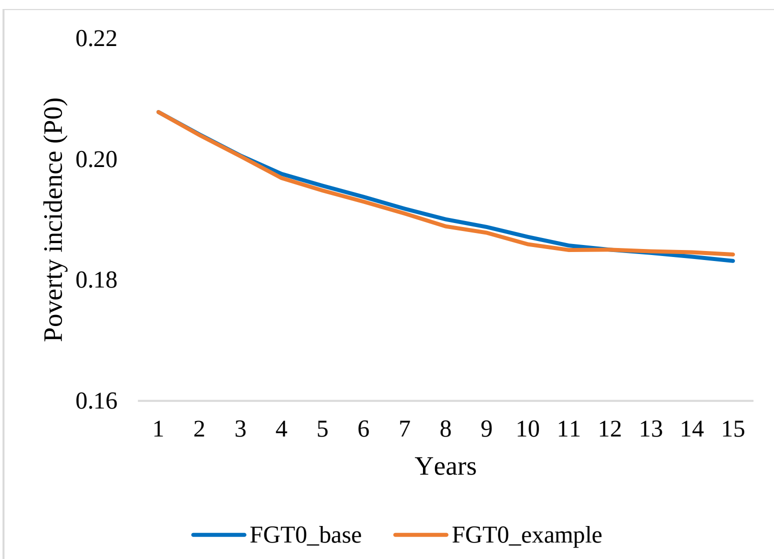
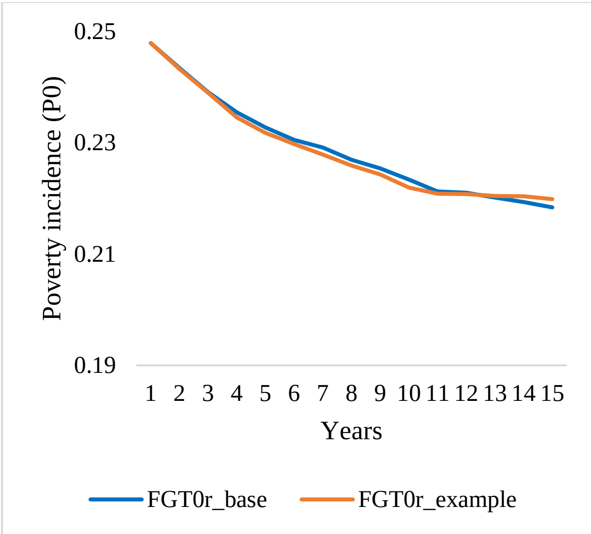


Figure 7. Population poverty incidence (P0) of the reference (FGT0_base) and scenario two (FGT0_sim) with increased feedstock productivity.



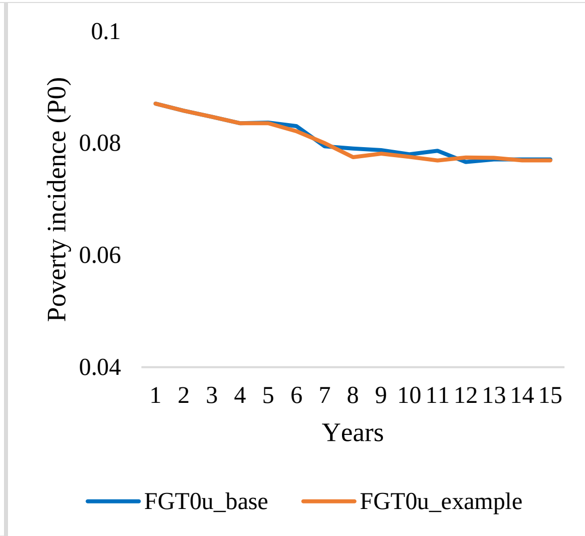


Figure 8. Rural poverty incidence (P0)

Figure 9. Urban poverty incidence (P0)

FGT0r_base is the poverty incidence under the reference, while FGT0r_sim is for scenario two. Note that the scales in Figures 4 and 5 are similar to allow comparison.

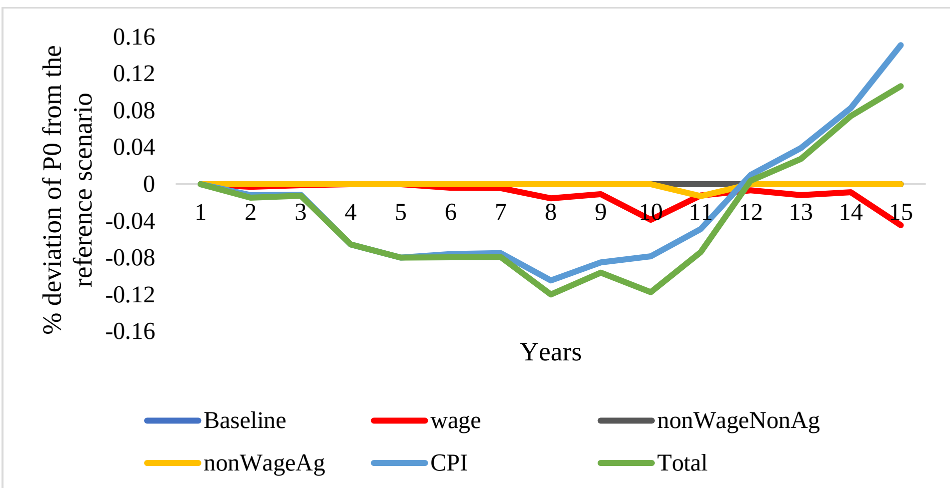


Figure 10. Scenario two - Poverty analysis decomposition by income source and the CPI

Change in income inequality

The Gini index is on an upward trend in the reference and ethanol scenarios; however, these trends do not differ across all three scenarios. Therefore, ethanol does not have a significant impact on income inequality.

4.3 Discussion of results

The growth in the sectoral and macroeconomic variables of the macro model drives the microsimulation model results. For example, in scenario one, while ethanol expansion drives up the output of the feedstock sectors, other land-based activities shrink. As a result, some commodity prices rise, and household income changes unevenly. Rising prices lead to a corresponding increase in the cost of the consumption basket of goods and, together with the change in income, they determine the effect on poverty. The negative effect in this scenario implies that the high consumer prices counteract the income benefits, diminishing any possible reduction in poverty. This argument is corroborated by the decomposition analysis of the poverty impact by income source and commodity prices. A significant percentage deviation of scenario one trajectory from the reference trajectory is attributed to changes in consumer prices (Figure 6). The values in this Figure coincide with those in the "population" column of Table C.1 of Appendix C. Conversely, higher wages suggest prospects of lower poverty levels, but this impact is negligible.

Cororaton and Timilsina (2012) investigate the impact of biofuel expansion on poverty. Despite an increase in the wage for rural unskilled labor in developing countries, poverty rises in South Asia and Sub-Saharan Africa, and slightly on a global scale. Regardless of the global scope of their study, the current study findings closely relate to theirs, adding to the literature that validates the danger of high food prices. In contrast, Arndt et al. (2010) found declining poverty under all biofuel scenarios— Jatropha biodiesel and sugarcane ethanol. Their study, however, is slightly different from the present analysis. They assume large volumes of biofuels for export, and their investigation involved exogenous land expansion. On the other hand, Boccanfuso et al. (2018) reported a reduction in poverty even in the absence of additional land, but those scenarios were based on a biofuel subsidy.

The pronounced change in rural poverty in the current study is due to the large portion of the rural population concentrated around the poverty line. Similar impacts are observed for the north and eastern regions. Given the marginal growth in income, the subsequent increase in food prices causes many to slip into poverty quickly. In comparison, the urban population is relatively small, and poverty changes are negligible because few are close to the poverty line. Moreover, the findings in the present study are not surprising given the high (46 percent) overall food and non-alcoholic beverages budget share of total household expenditures. Additionally, the SAM data for a selection of consumption items, including food staples, shows that rural households in lower-income quartiles spend more on consumption than urban households (except for the wealthiest urban households [34]) (See Tables B.1 and B.2 of Appendix B). Overall, the poverty increments are minimal. Nevertheless, they indicate the possible negative effects of first-generation biofuels, especially when feedstock crops are part of the food basket.

The reversal in the results under improved agricultural productivity proves the relevance of the food-biofuel debate. As Headey (2018) and others elucidate, whether or not rising food prices are beneficial will depend on how quickly agricultural supply and wages respond to price changes. It is evident that meager crop yields impede crop supply response to rising prices. The peculiarity of lower productivity cuts across most Sub-Saharan African countries. According to Goyal and Nash (2016), in Sub-Saharan Africa, area expansion contributes more to total agricultural output than the growth in yields. This situation implies a considerable potential to expand agricultural output through improved productivity and efficiency.

The overall findings show no significant implications for the income distribution. However, an important point to note is that biofuel (ethanol) promotion may instead exacerbate poverty in poor agriculture-dependent economies if existing agricultural bottlenecks are not addressed.

4.3 Sensitivity and Scenario analysis

I test the robustness of the results by performing a sensitivity analysis on key elasticity parameters in the CGE model. I vary the elasticity of substitution parameters between the capital and labor aggregates as well as their individual components at the lower level. As expected, the more elastic the substitution, the faster the growth in the macro variables. Nonetheless, the variations are not substantial because of the small ethanol sector, and these tests were not carried out in the distribution analysis.

In the scenario analysis, I set the CPI as the model numeraire and applied the results in the microsimulation model. The percentage changes in real consumption with respect to previous periods are slightly smaller than in scenario one, with the exchange rate as the numeraire (See Table 7). Nevertheless, the distribution pattern is similar in both cases. The microsimulation results show no impact on poverty. Poverty trends for the reference and scenario one are virtually constant, with no apparent differences between them (see Figure A.3 Appendix A). I, therefore, stick to the argument by De Janvry and Sadoulet (2002) of choosing a more neutral numeraire.

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[34] All urban households spend a small portion of their total household consumption budget on food than their rural counterparts. The food consumption budget for the highest quartile urban household is higher only in relative terms, but just a tiny portion of the household consumption budget. .

As I already mentioned, the small magnitudes of the effects do not permit some statistical validation of the difference between the reference and ethanol scenarios poverty trajectories. For example, I use Tables C.1 and C.2 in Appendix C to portray the differences. The values in the table are the calculated variations for the simulations from the reference case. Furthermore, a cross-examination of the growth incidence curves supports my research findings. For instance, regarding scenario one, Figure A.1 of Appendix A illustrates a reduction in consumption for all households, especially the population percentiles above the poverty line. This impact rises with the growth in ethanol output. In Figure A.2, increased crop yields benefit all households. Consumption among rural households rises in most percentiles, up to the 80th. However, urban households benefit more from lower food prices than their rural counterparts, with consumption rising up to 0.2 percent. Nonetheless, these benefits wane with the growth in ethanol production, as illustrated in the graphs for a later period.

Table 7. Percentage deviations in real consumption from the final base year value with CPI as the numeraire

	Real consumption
RuralQ1	0.07
RuralQ2	0.10
RuralQ3	0.10
RuralQ4	0.11
UrbanQ1	0.07
UrbanQ2	0.09
UrbanQ3	0.11
UrbanQ4	0.17

Q1 to Q4 correspond to the four income quartiles for both rural and urban households

5.0 Conclusion and policy implications

This study uses a dynamic CGE and a microsimulation model sequentially to examine the potential impact of ethanol production on poverty and income distribution in low-income countries. Using Uganda as the case study, it is found that there is a high potential for enhanced household income. However, the concomitant increase in commodity prices surpasses the growth in household incomes, resulting in rising poverty. While the increment in poverty is minimal, it reflects an imminent danger from rising food prices. I find that without improved crop yields, developing countries may fail to realize the full benefits of biofuels at the current productivity levels. Given the small magnitude of the impacts and close similarities in occupations across household groups, the categorization of households shows a rather blurry contrast in poverty levels. Nonetheless, poverty changes are more evident for the rural population, as well as the east and northern regions, because many have incomes close to the poverty line. On the other hand, the central and western regions exhibit minor variations. Lastly, it is the rural unskilled labor wage that rises most; nonetheless, the overall findings show no significant implications for the income distribution.

The key strength of this study is the evaluation of the impact of ethanol on poverty and the use of the Shapley method to decompose it by the input variables into the distributive analysis. This allows identification of the role of each variable in the evolution of poverty estimates and offers a clue to decision-makers on what to focus on. In the same vein, this study extends the applied research on biofuels versus food security and poverty. There are, however, three major limitations: First, the SAM used contains only cropland, failing to account for any land substitution across activities other than crop farming. Investigations can be extended to rich data on land with agricultural ecological zones. Second, capital is exogenously increased, assuming implicit investment incentives and mandatory ethanol use. Therefore, an explicit evaluation of the distributive impact of alternative policies to incentivize biofuel production would also be relevant. Third, a small volume of ethanol simulated generates smaller size effects that make some statistical tests not applicable. Most studies have effectively simulated larger target volumes to avoid such limitations [35]. However, I deliberately chose to assume less ambitious production that I consider feasible in the short to medium term. I partly circumvent the above shortcomings by relying on other tests referred to in the sensitivity analysis section. Despite these limitations, the study contributes to the debate of whether biofuels are pro or anti-poor and provides relevant insights, particularly in the policy formulation and implementation phase.

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Conflicts of interest:
I declare no conflict of interest.

Funding statement:
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[35] See Schuenemann et al. (2017) and Arndt et al. (2012).

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Appendix A

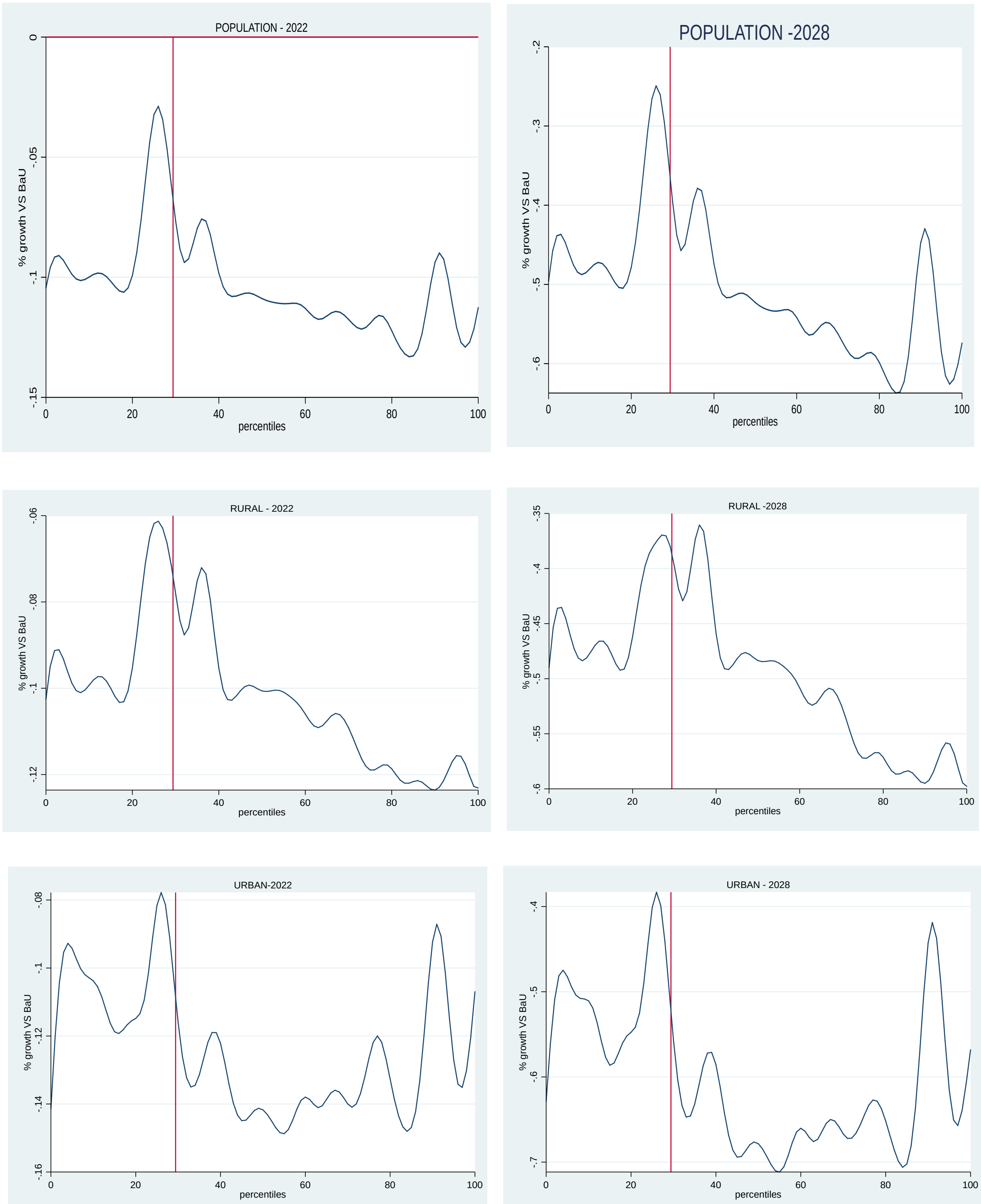


Figure A.1. Growth incidence curves for scenario one without crop productivity
The curves are for the population, rural, and urban, in two periods: 2022 and 2028

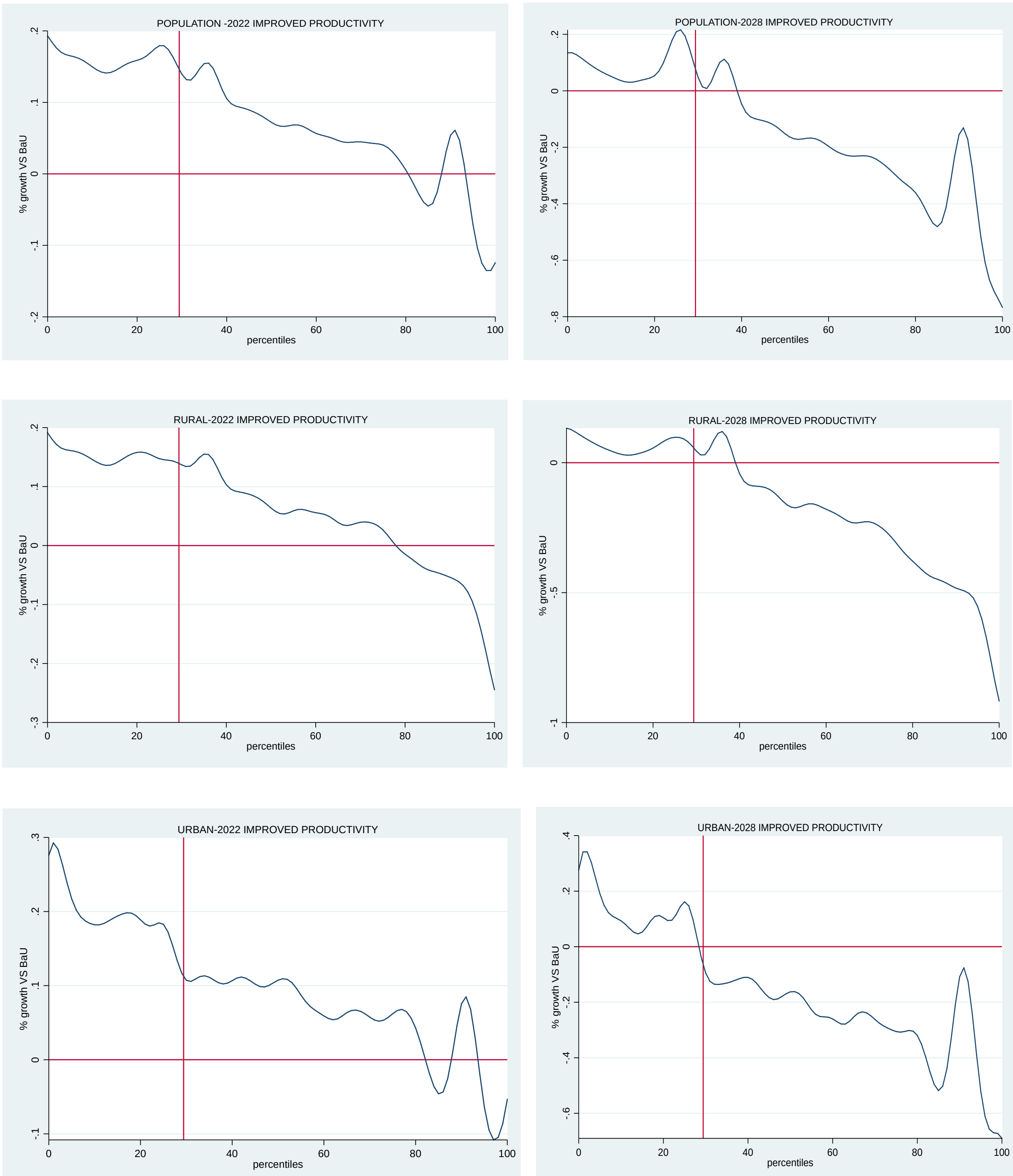
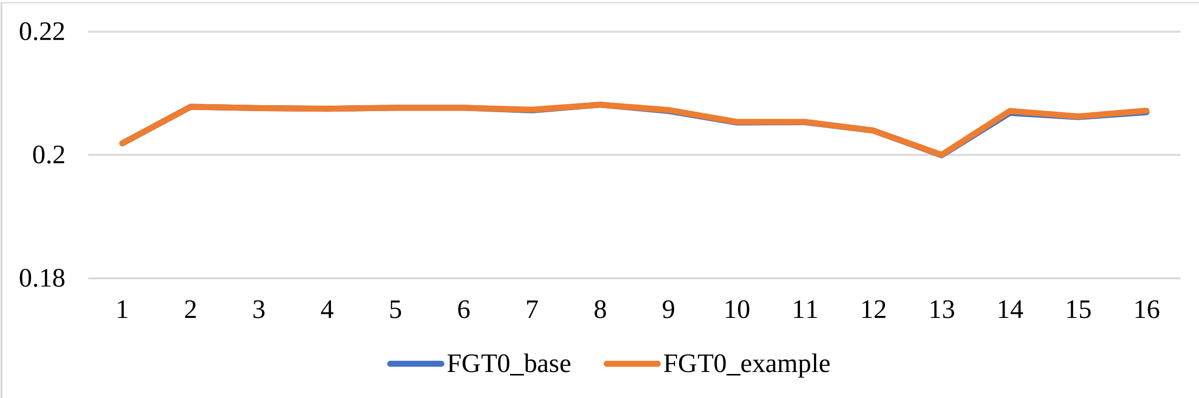
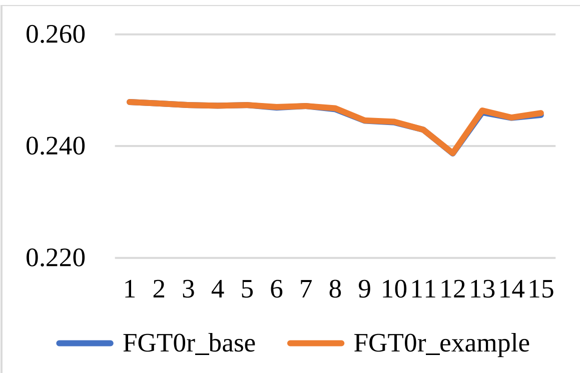


Figure A.2. Growth incidence curves for the scenario two with crop productivity
The curves are for the population, rural, and urban, in two periods: 2022 and 2028





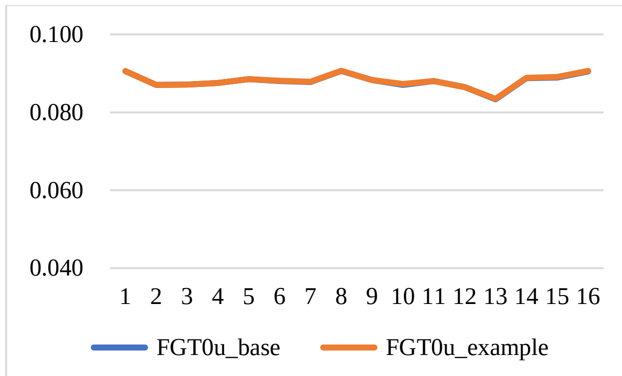


Figure A.3. Reference and scenario one poverty trends with the CPI as the model numeraire
FGT0, FGT0r, and FGT0u correspond to population, rural, and urban, respectively. "Base" represents the reference case and "example" scenario one.

Appendix B

Table B.1. Household commodity consumption across households from the SAM

		Rural	Urban
CgrainSeeds	Q1	10.39	2.67
	Q2	11.78	5.86
	Q3	10.91	9.30
	Q4	7.63	25.72
Cmaize	Q1	0.57	0.19
	Q2	0.52	0.29
	Q3	0.41	0.31
	Q4	0.19	0.29
Ccassava	Q1	1.98	0.36
	Q2	1.93	0.74
	Q3	1.44	0.89
	Q4	0.76	0.78
Csgrcane	Q1	0.00	0.00
	Q2	0.01	0.00
	Q3	0.01	0.01
	Q4	0.00	0.01
CanimalFarm	Q1	0.81	0.15
	Q2	1.51	0.56
	Q3	2.01	1.60
	Q4	1.86	4.53
Cfoodprodn	Q1	8.59	1.82
	Q2	10.31	4.65
	Q3	12.17	10.19
	Q4	10.49	23.94
Cmsugar	Q1	0.77	0.31
	Q2	1.10	0.90
	Q3	1.10	1.59
	Q4	0.75	2.35
	Q1	100.00	100.00

Table B.2. Household consumption expenditure and saving shares from the SAM

Household Category	Total income	Consumption Expenditure	Share Of consumption expenditure	Share of savings
RuralQ1	9390.856	8828.876	0.940157	0.03786
RuralQ2	11859.85	10769.79	0.908088	0.063022
RuralQ3	14314.8	12118.2	0.84655	0.099033
RuralQ4	19240.71	13770.28	0.715684	0.212896
UrbanQ1	1244.808	1161.113	0.932765	0.042498
UrbanQ2	3199.697	2854.127	0.891999	0.042498
UrbanQ3	7246.142	5976.616	0.8248	0.105982
UrbanQ4	31971.44	19534.9	0.611011	0.2581

Table B.3. Commodity classification and mapping

Classification in the Survey data	Classification in the SAM	Description
Clothes and Footwear	Clothes and Footwear	Clothing and footwear expenditure
Health	Health	Health services
Furniture, equipment, and home maintenance	Cforestry	Forestry products
Communication	Communication	Communication services
Recreation and culture	Recreation and culture	Recreation and culture services
Education	Education	Education services
Food and beverages outside home	CdrinkSmokes	Alcoholic beverages and tobacco
Food and beverages	Cfoodprodn	Processed food
	CgrainSeeds	Other grains like rice
	Cmaize	Maize flour
	Ccassava,	Cassava flour
	CanimalFarm,	Animal and poultry products
	Cmsugar,	Sugar
	Cfishing,	Fish and fish products
	Ccashcrops	Other cash crops like vanilla, tea
	Csgrcane	Sugarcane
Housing, water, electricity, and gas	CelecHydro	Hydroelectricity
	CelecSolar	Solar electricity
	CelecThermal	Thermal electricity
	CelecOther	Other sources of electricity
	Cfirewood	Woodfuel
	Ccharcoal	Charcoal
Transport	COPetroleumn	Petroleum products like diesel, kerosene
	Cblend	Blended gasoline with ethanol
	Ctransport	Other transport services
Diverse goods and services	Cothermanufacture	Other manufactured goods
	Cchemicals	Chemicals like washing detergents
None-consumption expenditure	Cpubadminother government	Public administration services by
	Cfinservices	Financial services
	Ctrade	Trade services
	Cotherservice	Other services

Table B.4 Labor classification and mapping

Classification in survey data	Classification in the SAM	Description
Skilled labor ($> 7\ years\ of\ school$)	Semrm	Semi-skilled male rural
	Semrf	Semi-skilled female rural
	Semum	Semi-skilled male urban
	Semuf	Semi-skilled female urban
	Skrm	Skilled male rural
	Skrf	Skilled female rural
	Skum	Skilled male urban
	Skuf	Skilled female urban
	Hsrm	Highly skilled male rural
	Hsrf	Highly skilled female rural
	Hsum	Highly skilled male urban
	Hsuf	Highly skilled male urban
Unskilled labor ($\leq 7\ years\ of\ school$)	Unsrm	Unskilled male rural
	Unsrf	Unskilled female rural
	Unsum	Unskilled male urban
	Unsuf	Unskilled female urban

Table B.5 cumulative percentage changes in the wage for skilled and unskilled labor

	Skilled	Unskilled		
	Population	Population	Rural	Urban
1	0	0	0	0
2	-0.01	0.009	0.013	-0.01
3	-0.02	0.019	0.027	-0.02
4	-0.03	0.03	0.041	-0.02
5	-0.04	0.04	0.056	-0.03
6	-0.05	0.051	0.072	-0.04
7	-0.06	0.063	0.088	-0.04
8	-0.06	0.075	0.104	-0.05
9	-0.07	0.087	0.122	-0.05
10	-0.08	0.1	0.139	-0.06
11	-0.09	0.114	0.158	-0.06
12	-0.10	0.127	0.177	-0.06
13	-0.10	0.142	0.197	-0.07
14	-0.11	0.157	0.218	-0.07
15	-0.12	0.173	0.241	-0.07

Appendix C

Table C.1 Deviations of scenario one from the reference trajectory assuming current feedstock yields

time	Population	Rural	Urban	Central	East	North	West
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-
3	0.003	0.003	-	0.009	-	-	-
4	0.090	0.120	-	-	0.121	0.000	0.233
5	0.055	0.067	0.016	0.059	0.059	0.108	-
6	0.029	0.038	0.003	0.002	0.033	0.095	-
7	0.097	0.053	0.232	0.045	0.132	0.061	0.150
8	0.092	0.122	0.000	0.045	0.347	0.004	0.025
9	0.153	0.179	0.073	0.061	0.383	0.176	0.004
10	0.173	0.196	0.104	0.062	0.360	0.162	0.118
11	0.240	0.274	0.137	0.083	0.434	0.356	0.123
12	0.310	0.323	0.271	0.112	0.644	0.339	0.169
13	0.343	0.339	0.355	0.105	0.863	0.314	0.109
14	0.380	0.423	0.248	0.115	0.824	0.525	0.107
15	0.399	0.433	0.296	0.175	0.829	0.503	0.130

Table C.2 Deviations of scenario two from the reference trajectory with increased feedstock yields

time	Population	Rural	Urban	Central	East	North	West
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.015	-0.020	0.000	0.000	-0.053	-0.006	0.000
3	-0.013	-0.015	-0.005	-0.004	-0.012	-0.040	0.000
4	-0.065	-0.087	0.000	-0.012	-0.081	-0.197	0.000
5	-0.080	-0.101	-0.015	-0.006	-0.219	-0.106	0.000
6	-0.080	-0.075	-0.093	-0.046	-0.209	-0.053	-0.009
7	-0.079	-0.124	0.056	-0.025	-0.287	-0.086	0.075
8	-0.120	-0.107	-0.157	-0.104	-0.130	-0.269	-0.004
9	-0.096	-0.108	-0.061	-0.003	-0.201	-0.165	-0.037
10	-0.117	-0.141	-0.047	-0.038	-0.220	-0.235	-0.005
11	-0.074	-0.042	-0.171	0.000	-0.230	-0.015	-0.048
12	0.004	-0.021	0.078	0.000	0.015	-0.031	0.024
13	0.027	0.026	0.031	0.026	0.066	0.037	-0.017
14	0.074	0.105	-0.020	0.039	0.055	0.233	0.001
15	0.106	0.148	-0.019	0.099	0.120	0.229	-0.001

Miria Nakamya was born on 11th November 1979 and grew up in Buwenge, Jinja District, Uganda. She holds a Bachelor's degree in Economics obtained in 2009 from Makerere University, Uganda. She also holds a Master's degree in Economics from the same university, obtained in 2014 under the African Economic Research Consortium (AERC) Collaborative Masters Program (CMAP). Miria is currently a Lecturer at Makerere University Busines School, Uganda.

In a computable general equilibrium framework and microsimulation modeling, this thesis evaluates the policies to promote biofuels in developing countries and examines the impacts in the realms of sustainable development in four related but independent research papers.

Drawing from the research findings, efforts to promote ethanol (biofuels) should be geared toward both the processors and the agricultural sector. Revealed emission-reducing potential shows no danger from grassland conversion, but forest land should be avoided.

Ethanol production has the potential to cause growth and reduce poverty in developing countries; however, these benefits may be elusive at the current crop yields.

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