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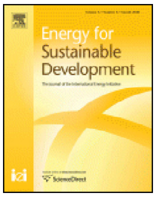

How sustainable are biofuels in a natural resource-dependent economy?

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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

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[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.

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

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

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[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

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[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).

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

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).

$$ET_{crop} = kc * ET_0 \tag{5}$$

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.

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

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.

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

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]

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[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.

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

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[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.

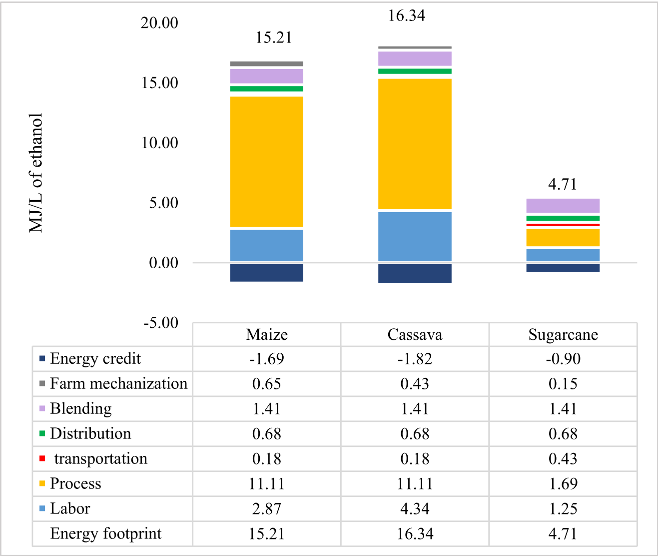
[19] Note that for ethanol volumes up to a 10% blend level permit an equivalence of the units of gasoline and ethanol (Macedo et al., 2008).

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

[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

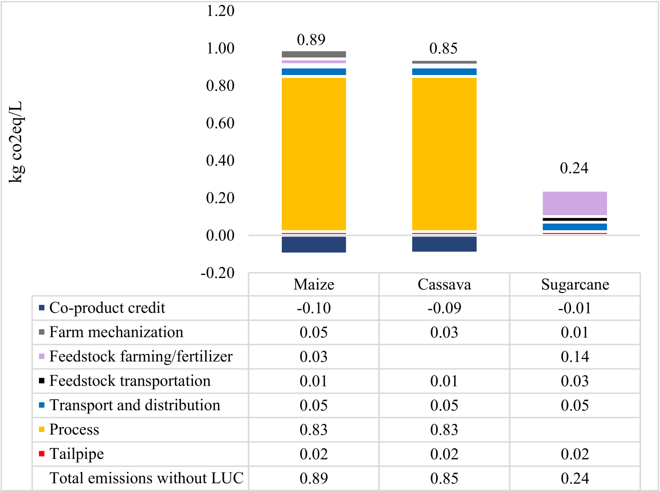
Fig. 1 depicts processing as the most energy-intensive stage for maize and cassava ethanol, constituting about 73 and 68% of the total energy requirements for maize and cassava ethanol, respectively. The two pathways also have significant labor-energy intensities per liter than sugarcane. Nonetheless, 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 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.



	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.

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.

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

[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%	

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.

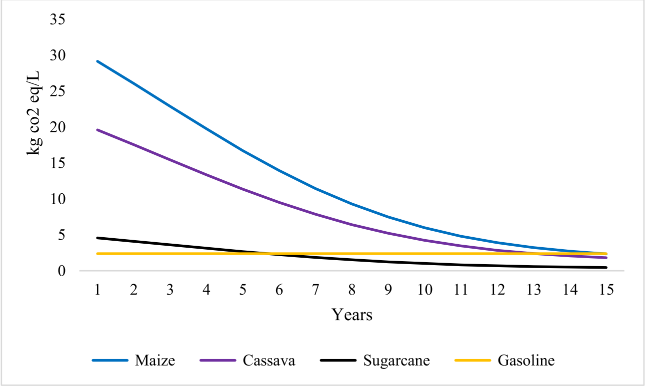

Fig. 3. Emissions per liter of ethanol and gasoline (All feedstock on 26 t CO2eq/ha grassland).

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

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[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 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.

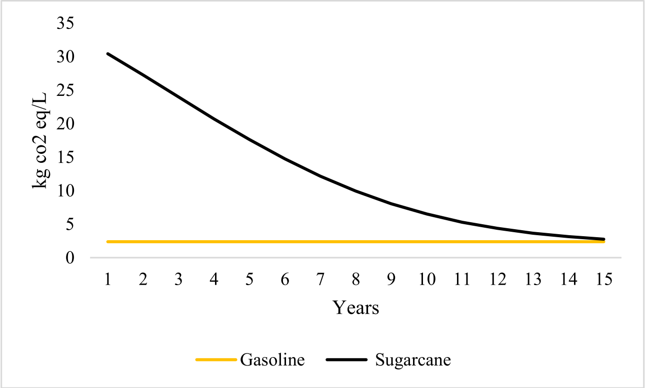

Fig. 4. Emissions per liter of sugarcane ethanol and gasoline (All sugarcane on 151 t CO2eq/ha forestland).

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.

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[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.

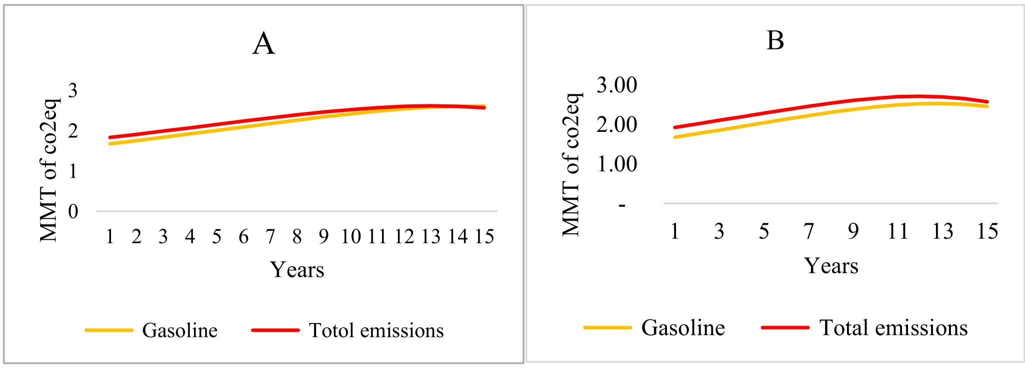

Fig. 5. Plot of total and gasoline emissions in million metric tons (MMT) of carbon dioxide equivalent.

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

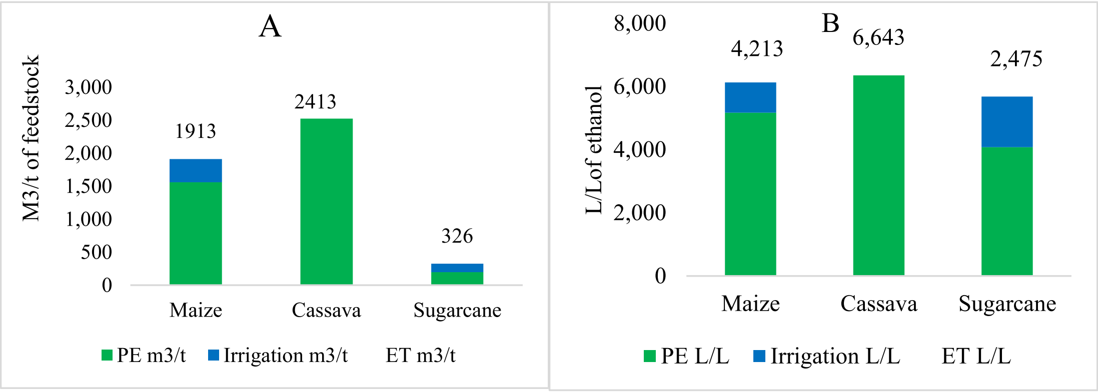

Fig. 6. Water footprint in cubic meters (m^3) per metric ton (t) and liters of water per liter of ethanol (L/L) before allocation to co-products.
ET refers to evapotranspiration and PE precipitation (green water). Irrigation accounts for the blue water in agriculture. ET m^3/t and irrigation m^3/t divides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

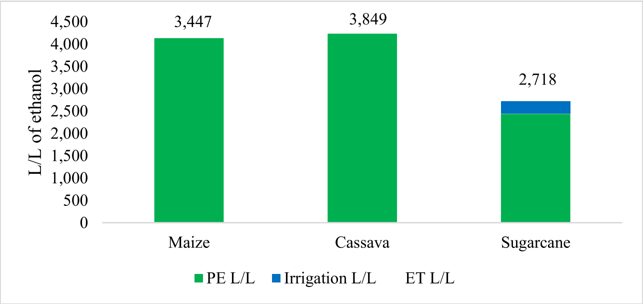

Fig. 7. Water footprint in liters of water per liter of ethanol (L/L).
ET refers to evapotranspiration and PE precipitation (green water). Irrigation accounts for the blue water in agriculture.

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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