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Sustainable Production of Food and Bioenergy: Techno-economic and Environmental Assessment of Sugarcane Ethanol and Livestock Integration

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Despite their advantages when replacing fossil fuels, biofuels have faced some concerns related to their expansion within the so-called “food vs. bioenergy” debate. This debate relies on the premise that the use of food crops and/or the increase of land use for bioenergy production would affect food availability and price. Nevertheless, it is worth to mention that livestock production is the largest anthropic use of land resources worldwide. In Brazil, livestock production mainly consists of extensive management with low technology level, which results in a low average productivity. The intensification of this system would release pasture areas to expand cropland for biofuels production. In this way, the integration of sugarcane ethanol and livestock production would allow taking advantage of the synergies between both systems; for instance, using sugarcane agroindustrial residues as animal feed ingredients in feedlot systems. In addition, ethanol production from lignocellulosic feedstock (second-generation process) is also a possible solution towards a productive land use, since a larger amount of biofuels can be produced per crop area. This work focuses on the sustainability assessment of a first- and second-generation (1G2G) ethanol facility that produces animal feed using sugarcane by-products integrated to livestock production in feedlots. The Virtual Sugarcane Biorefinery (VSB) – a computer framework that simulates the entire production chain and assesses the sustainability impacts of different biorefinery alternatives/routes – was used in this work. This paper indicates that the integration of a future 1G2G sugarcane mill with intensive livestock system may be a feasible alternative. Regarding the economic performance, verticalization of a mill with intensive livestock is preferable when compared to extensive cattle production. Integrated scenarios also have environmental advantages, such as the production of more outputs using the same area, as well as more efficient technologies that may represent lower emissions. In addition, this paper revealed that it is possible to sustainably produce biofuels without displacing food crops or livestock production, which otherwise could advance, for example, in forest areas.

1. Introduction

Biofuels have been pointed out as a sustainable alternative to replace fossil fuels, mostly because of their potential to reduce greenhouse gases emissions and to increase energy security. The large-scale production of ethanol, as substitute for gasoline in Otto cycle engines, is an example of a successful transition from fossil to a renewable energy source. Ethanol is mostly produced through sugars fermentation (first generation, “1G”, process) from corn and sugarcane, respectively, in United States and Brazil that are the major producers in the world. Ethanol is also produced from lignocellulosic materials, such as agroindustrial residues and energy crops, in the so-called second-generation (2G) process, which is already deployed at commercial scale in few plants installed worldwide, including two plants in Brazil (Junqueira et al., 2017).

The environmental benefits of ethanol use as fuel have been demonstrated in several works. Junqueira et al. (2017) showed that sugarcane ethanol (both 1G and 2G) can reduce greenhouse gases (GHG) emissions more than 80 % compared to gasoline. Wang et al. (2014) showed that even negative values for GHG emissions can be achieved if credits from electricity replacing natural-gas based energy are considered.

Despite these benefits, the expansion of biofuels has faced some concerns related to land availability and food security ("food vs. bioenergy" debate), which is based on the premise that the use of food crops and/or the increase of land use for bioenergy production would affect food availability and price (Leal and Nogueira, 2014). The authors also pointed out that not only each biofuel has a different impact, but its impact is highly dependent on the production model and local conditions. In terms of land use, sugarcane is responsible for only 1.1 % of the total area of Brazil. Native vegetation roughly accounts for 60 %, followed by pasture with around 20 %. In Brazil, most of the livestock (cattle) production is based on pasture-based system (extensive management) with low average productivity, around 1 head per hectare (Souza, 2017). Worldwide, livestock is the largest user of land resources, with grazing land and cropland dedicated to the production of feed representing almost 80 % of all agricultural land use (FAO, 2009).

In this context, integration of sugarcane ethanol production with livestock production can improve overall sustainability, by taking advantages of their synergies through intensification of livestock production (feedlots) and use of agroindustry by-products (e.g. *in natura* and pretreated bagasse, yeast and molasses) (Taube-Netto et al., 2012). In addition, released areas from livestock production would be available to expand cropland for biofuels production (Berndes et al., 2016), thus decreasing potential negative impacts of agriculture expansion. It is worth to mention that these two sectors not only play an important role in the Brazilian economy, but also worldwide, since the country is the second largest producer of beef and ethanol (Souza, 2017). This work presents a techno-economic and environmental assessment of scenarios for expansion of ethanol production through second-generation ethanol production and integration with livestock system.

2. Methodology

2.1 Modeling of the sugarcane production chain

The modeling of sugarcane chain was performed using the Virtual Sugarcane Biorefinery – VSB (VSB, 2018), which is a computer platform that simulates the entire production chain (including agricultural, industrial and logistics and use stages) and assesses the sustainability impacts of different biorefinery alternatives/routes. Within the VSB, the agricultural modeling is carried out using Canasoft model, which quantifies inputs and outputs of each stage of the biomass production. The simulation of the industrial process is performed with Aspen Plus® v. 8.6 (Aspentech, 2018) through mass and energy balances. In this work, a sugarcane mill that produces sugar, ethanol (1G and 2G) and electricity was considered as base case. Figure 1 presents a block-flow diagram for this process and main technical parameters are presented in Table 1. Further description of the sugarcane production system and industrial conversion can be found in Bonomi et al. (2016a). Second generation parameters are based on steam explosion pretreatment and enzymatic hydrolysis considering long-term technology defined in Bonomi et al. (2016b).

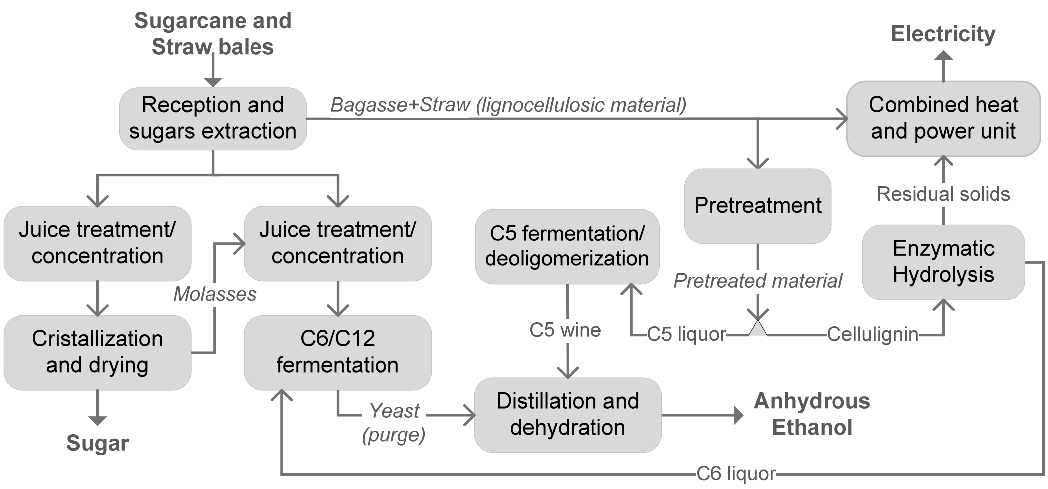

Figure 1: Block-flow diagram of the sugarcane mill (base case). Main inputs and products are highlighted in bold. Sugarcane by-products with potential use in animal feed are in italic.

Table 1: Main parameters for the sugarcane mill.

Parameter	Value	Parameter	Value
Sugarcane average yield ($t.ha^{-1}$)	80.0	Pretreatment conditions (°C / min)	210 / 5
Straw recovery (%)	50.0	Enzymatic hydrolysis efficiency (%)	80.0
Industrial operation ($d.y^{-1}$)	200	Enzymatic hydrolysis conditions (°C / h)	65 / 36
Sugar extraction efficiency (%)	96.0	C6/C12 fermentation efficiency (%)	89.5
Sugar overall recovery as sugar (%)	76.5	C6/C12 fermentation time (h)	9
Boiler efficiency (%)	87.7	C5 fermentation efficiency (%)	85.0
Turbine efficiency (%)	85.0	C5 fermentation time (h)	24

2.2 Modeling of livestock production system

In Brazil, livestock production is mainly based on extensive pasture with cattle grazing all year long. Extensive management, in native or cultivated pastures, presents low stocking rate; in São Paulo state, stocking rate in the wet season is around 2.8 heads per hectare ($hd.ha^{-1}$), while in the dry season, it is around 1.0 $hd.ha^{-1}$. During dry season, cattle need feed supplementation to avoid weight loss, or can be finished in feedlots (Souza, 2017). This work focuses on the finishing period (fattening) of cattle, comparing extensive pasture and feedlots. The VSB platform was adapted to model livestock production system. The assumed values for Nelore (the main breed for beef production) for initial and final weight were 360 and 480 kg, respectively. In pasture, the finishing period usually lasts for 365 days with cattle grazing with balanced mineral salt supplementation (0.1 % of cattle live weight), with an average daily gain (ADG) lower than 0.4 $kg.hd^{-1}.d^{-1}$. For feedlots, it is considered an ADG of 1.0 $kg.hd^{-1}.d^{-1}$ during 120 days and cattle are fed with ration composed by sugarcane by-products and other ingredients purchased at the market.

2.3 Assessment of techno-economic and environmental impacts

Within VSB, the techno-economic analysis is based on the approaches from the Engineering Economics, utilizing a discounted cash flow analysis. The cash flow analysis takes into account capital expenditures (investment in buildings, equipment, land, infrastructure, working capital to invest in cattle purchase, etc.), revenues (based on market prices of the main outputs such as ethanol, sugar, electricity and cattle live weight), and operating costs (expenditures associated with feedstock, labor, maintenance, chemicals, utilities, vaccines, fertilizers, etc.).The main calculated impacts are internal rate of return (IRR), net present value (NPV) and ratio between NPV and investment (profitability index). This analysis considers a greenfield project using December 2016 as reference data, linear depreciation of 10 years, 25 years of expected project lifetime and discount rate of 12 % per year (real rate). Table 2 shows the composition and cost of feed ingredients considered in the feedlot system. Table 3 presents costs and prices for the main feedstock/inputs and outputs, based on average values obtained from historical data. Two approaches were considered in the analysis: (1) vertical – where the sugarcane mill and livestock production are part of the same enterprise (animal feed is an intermediate flow, not a product); (2) horizontal – the sugarcane mill sells the animal feed to the owner of the livestock production enterprise at US$ 59.0 t^{-1}, value estimated based on the average daily gain and market price of a commercial ration (Vale do Rosário mill, personal communication, 2017).

Table 2: Composition of animal feed for a daily intake of 21.91 $kg.hd^{-1}.d^{-1}$ and cost of external ingredients (Souza, 2017).

Ingredients	Daily intake ($kg.hd^{-1}.d^{-1}$)	Content (%, wet basis)	Cost (US$.$t^{-1}$ of ingredient)
Sugarcane by-products			
Treated lignocellulosic material	11.9	54.5	*
in natura lignocellulosic material	0.90	4.1	*
Wet yeast	4.89	22.3	*
Molasses	0.39	1.8	*
External products			
Corn Grain	2.53	11.5	179
Soybean Bran	0.91	4.2	352
Urea	0.08	0.4	997
Mineral Salt	0.28	1.3	659
Rumensin	0.003	0.01	388

* The use of sugarcane by-products for production of animal feed reflects in the reduction on ethanol and electricity outputs, mostly due to the use of molasses and lignocellulosic material.

Table 3: Costs and prices for the main feedstock/inputs and outputs. Exchange rate: US$ 1.00 = R$ 3.35.

Product	Cost/price (US$)	Product	Cost/price (US$)
Unfinished cattle (live weight)	1.41 kg^{-1}	Sugar	0.38 kg^{-1}
Finished cattle (live weight)	1.31 kg^{-1}	Ethanol	0.51 L^{-1}
Balanced mineral salt	0.66 kg^{-1}	Electricity	57.9 MWh^{-1}

The environmental analysis employed the Life Cycle Assessment (LCA) technique, which considers the whole production, transportation and use chain for the assessment of the impacts (Bonomi et al., 2016a). In this work, environmental results are presented in terms of climate change impact for ethanol (per MJ) and meat (per kg of live weight). Sugarcane mill impacts were allocated between products (sugar, ethanol, electricity and by-products used in the ration) considering their participation on revenues (economic allocation). Although land use change (LUC) issues appear on discussions about the environmental impacts of biofuels and livestock production, the methodologies accounting for LUC have significant controversies and uncertainties. Despite the great progress in recent years, there is still no methodological consensus, and the results of improved models indicate increasingly smaller effects in terms of these emissions for Brazil. For this reason, this study does not consider LUC emissions in the results.

2.4 Scenarios definition

This work considers three scenarios to assess impacts of intensification of livestock production and production of animal feed by a sugarcane mill. Scenarios definition is illustrated in Figure 2.

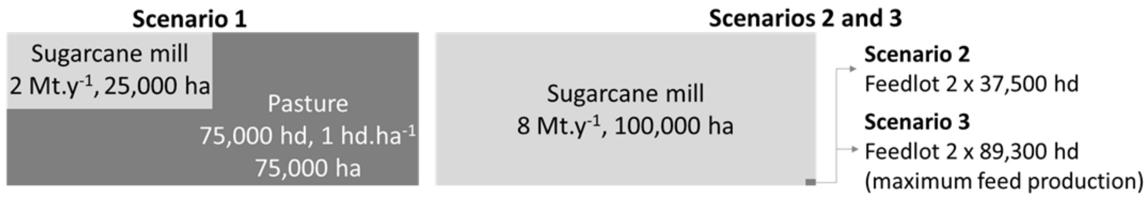

Figure 2: Configuration of evaluated scenarios for sugarcane and livestock production.

3. Results and discussion

Sugarcane costs (in wet basis) calculated by CanaSoft were US$ 20.72, US$ 22.29 and US$ 22.25 for Scenarios 1, 2 and 3, respectively; while, straw recovery costs (in dry basis) were US$ 25.84, US$ 27.91 and US$ 27.91. Both sugarcane stalks and straw costs are higher for Scenarios 2 and 3, compared to Scenario 1, mostly due to larger transport distances associated to the higher processing capacity. Small differences in sugarcane costs between Scenarios 2 and 3 are due to larger amount of vinasse and boilers ashes to be disposed at field when sugarcane by-products are not used for animal feed production. The main product outputs for each scenario is presented in Table 4. When comparing Scenario 3 with maximum feed production (limited by yeast availability) to Scenario 1 (without feed production), per tonne of cane, there is a reduction of 8.2 % in ethanol production and 5.4 % in surplus electricity due to the use of sugarcane by-products.

Based on the discounted cash flow analysis (Figure 3A), it is possible to observe the difference among industrial scenarios with horizontal approach. Considering the effect of economies of scale, Scenarios 2 and 3 (8 million tonnes capacity each) are related to higher internal rates of return and profitability indexes (NPV/investment). As Figure 3B shows, Scenario 2 has a higher IRR when compared to Scenario 3 when considering a cattle feed selling price of US$ 59 t^{-1}. On the other hand, according to the sensitivity analysis of IRR against cattle feed selling price shows that Scenario 3 may have a higher IRR than Scenario 2 when the feed price is above US$ 83 t^{-1}.

Table 4: Product outputs in the evaluated scenarios.

Product	Scenario 1	Scenario 2	Scenario 3
Sugar (10^6 $kg.y^{-1}$)	102.8	411.1	411.1
Ethanol (10^6 L. y^{-1})	185.7	716.2	681.5
Surplus electricity ($GWh.y^{-1}$)	125.1	489.5	473.5
Animal feed (kg. t_{cane}^{-1})	-	197.2	469.6
Meat (10^6 $kg.y^{-1}$)	36.0	36.0	85.7

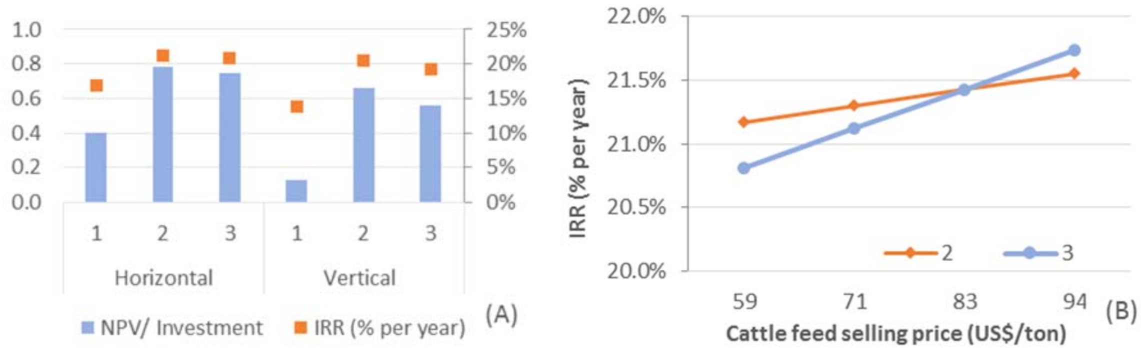

Figure 3: Techno-economic results: (A) NVP/investment and IRR for evaluated scenarios; (B) Sensitivity analysis of cattle feed price in the IRR of the sugarcane mill (horizontal approach).

When it comes to the effects of verticalization on the sugarcane industry, it is important to highlight that Scenario 1 would reduce its IRR from 17 % to 13 % per year. The explanation is that Scenario 1 is associated with extensive pasture system whose net present value is negative (- US$ 85 million) as well as its profitability index (-1.71). Such negative performance of extensive cattle production can be attributed to the low yields of extensive management as well as to the high opportunity cost of land in SP State (US$ 154 ha^{-1} for pasture and US$ 298 ha^{-1} for sugarcane). Figure 3 also indicates that Scenarios 2 and 3 are associated with intensive cattle production whose indicators are more economically attractive. According to the simulations of different cattle production intensive systems associated with Scenarios 2 and 3, it was possible to calculate that both cattle production systems have the same economic performance (IRR of 20 % and profitability index of 0.75 for both). Therefore, the differences between Scenarios 2 and 3 are mostly related to the differences of the sugarcane industry scenarios. In the vertical approach, it was calculated that Scenario 3 would only be more attractive than Scenario 2 in case finished cattle price was higher than US$ 1.76 (instead of US$ 1.31 per kg).

The environmental impact results are presented in Table 5 and indicate that the increase of scale slightly worsen the environmental results of sugarcane products, owing to higher biomass transportation distance to the industry. On the other hand, the intensification of cattle production reduces the impact of beef production, mainly due to the reduction on the cattle finishing period (from 365 days in Scenario 1 to 120 days in Scenarios 2 and 3), decreasing the effects of enteric fermentation emissions.

It should be noted that these results are valid per unit of product. Slightly worse results per unit of output do not necessarily indicate that one biorefinery scenario will have worse impacts than another, since production volumes are significantly different across scenarios. To assess the overall effect of all products originating from the same area (100,000 ha), the benefits of these products were quantified in relation to reference products: gasoline for ethanol, average Brazilian electricity grid for electricity, and extensive pasture with cattle grazing all year long (as defined in Scenario 1) for beef. The total avoided emissions are presented in Figure 4. The figure indicates that although impacts per MJ of ethanol are slightly worse in Scenarios 2 and 3, the benefit from the roundly 4 times higher production of this biofuel is highly advantageous. This comparison also shows that although the Scenario 3 is slightly hampered by lower ethanol volumes (due to bagasse diverted to cattle feed), beef production offsets this effect.

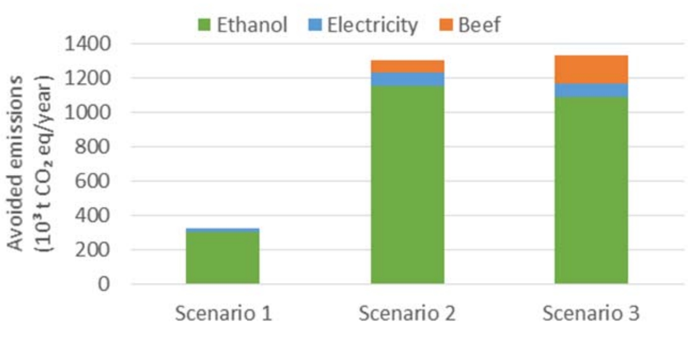

Figure 4: Total avoided emission due to ethanol, electricity and beef production in an area of 100,000 hectares.

Table 5: Environmental impacts per product in different considered scenarios.

Product	Unit	Scenario 1	Scenario 2	Scenario 3
Ethanol	g CO_2 eq.MJ^{-1}	15.1	15.4	15.7
Sugar	g CO_2 eq.kg^{-1}	231.4	253.6	259.4
Electricity	g CO_2 eq.kWh^{-1}	35.6	39.0	39.9
Beef	kg CO_2 eq.kg^{-1}	13.5	11.6	11.6

4. Conclusions

The results shown in this study indicate the feasibility of integration of biofuel production in a future 1G2G sugarcane mill with an intensive livestock system. Increased scale of the sugarcane mill proved to be the better economic and environmental alternative, as well as intensive livestock system when compared to extensive cattle production. Slightly higher biomass production costs and environmental impacts of sugarcane products in large-scale plants are offset by a significantly higher production using the same area, while cattle production in intensive system benefits from lower production costs and lower finishing time. These results revealed that it is possible to sustainably increase biofuels production without displacing food crops or livestock production, which otherwise could advance, for example, in forest areas.

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