

Economic Optimization of Sugarcane-Livestock Integration for Bioenergy Expansion in Brazil

Igor L. R. Dias^{a*}, Ana C. M. Jimenez^b, Terezinha F. Cardoso^b, Tassia L. Junqueira^b, Geraldo B. Martha Jr^c, Adriano P. Mariano^d, Marcelo P. Cunha^d, Antonio Bonomi^b

aFaculdade de Engenharia Química (FEQ), Universidade Estadual de Campinas (Unicamp), Av. Albert Einstein, 500, CEP 13083-852, Campinas - SP, Brasil.

bLaboratório Nacional de Biorrenováveis (LNBR), Centro Nacional de Pesquisa em Energia e Materiais (CNPEM), CEP 13083-970, Campinas - SP, Brasil.

cEmbrapa Agricultura Digital, Av. Dr. André Tosello, 209 - Cidade Universitária, 13083-886, Campinas - SP, Brasil.

dInstituto de Economia (IE), Universidade Estadual de Campinas (Unicamp), R. Pitágoras, 353 - Cidade Universitária, 13083-857, Campinas - SP, Brasil.

i261185@dac.unicamp.br

Due to the expansion of ethanol production, debate on conflicting issues regarding land use competition between biofuels and food production is raised. Integrated sugarcane/livestock systems could potentially facilitate the expansion of ethanol production without putting crop and/or livestock production at risk and displacing areas covered with natural vegetation. This study compares and analyses the profitability of (i) a sugarcane ethanol distillery (producing ethanol and bioelectricity) and a typical livestock system without integration and (ii) an integrated system producing the same output of ethanol and beef with half of the area. Therefore, this study developed metamodels to evaluate sugarcane/livestock integration from a techno-economic perspective, aiming to maximize the profitability (Net Present Value relative to investment) of this integrated system. The obtained metamodels adequately represented the proposed systems and proved to be useful tools for simplifying complex models and providing insights into the decision-making process. Considering the assumptions adopted in this study, it was observed that the system with integration presents better economic results. Furthermore, sensitivity analysis of land rent revealed that sugarcane and livestock integration becomes economically attractive and viable under the analyzed conditions for values exceeding 258 US\$/ha. The generated metamodels also allow other scenarios to be analyzed to find other economically and environmentally attractive solutions for the expansion of ethanol production in Brazil, utilizing pasture areas.

Keywords: Biorefineries, Beef cattle production, Experimental Design, Optimization metamodels, Food versus biofuels

1. Introduction

The production of biofuels, particularly ethanol, has been encouraged in Brazil since last century (Cortez et al., 2016). Due to the expansion of ethanol production, conflicting issues regarding land use competition between biofuels and food production are raised. Recently, the Brazilian Government launched the Brazilian National Biofuel Policy (RenovaBio) and the second phase of the Low-Carbon Emission Agriculture Plan (Plano ABC+). These initiatives aim: (i) to encourage the increase in production and consumption of biofuels over fossil fuels and (ii) to foster sustainable agricultural intensification practices (such as the recovery of low-productive pastures and the promotion of crop-livestock-forestry integration). The goal is to expand agricultural output while simultaneously reducing greenhouse gas (GHG) emissions and lessening pressures to increase cropland (ANP, 2020; MAPA, 2021). Integrated sugarcane-livestock systems could potentially facilitate the expansion of ethanol production without putting crop and/or livestock production at risk and displacing areas covered with natural vegetation (Souza et al., 2019).

Considering these facts, this study aims to assess whether promoting integration between the sugarcane and beef cattle systems is economically advantageous. For this purpose, metamodels for sugarcane production, ethanol mill, and beef cattle production were optimized.

2. Methodology

2.1 System description

Two systems were compared in this study (Figure 1):

(A) System without integration, consisting of:

(A1) Sugarcane ethanol distillery system: This system involves the production and transportation of sugarcane to a first-generation biorefinery and its processing to produce ethanol. The bagasse and sugarcane straw recovered are used in the boiler, generating steam to produce bioelectricity. The ethanol, surplus electricity and part of the excess bagasse produced in the biorefinery are sold. In the sugarcane reform area, soybeans are grown, and their grains are sold, with the revenue added to the system. Additionally, Decarbonization Credits (CBIOs) are sold, increasing biorefinery revenue. The area allocated for the industrial sector of the biorefinery is negligible.

(A2) Beef cattle production on pasture: This typical system exclusively involves fattening beef cattle on pasture without feed supplementing. Pasture establishment is considered at the implementation of operations and pasture maintenance is carried out over subsequent years through fertilization with urea, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O). Cattle heads are purchased and subsequently resold annually after completing the fattening process, which occurs during the rainy season in Brazil (between September and March). The productive pasture area is considered equivalent to the area allocated for sugarcane production in the biorefinery in A1.

(B) System with integration, consisting of:

(B1) Sugarcane ethanol distillery system: This system has the same operations and ethanol production as A1. However, in this integrated system, a portion of the bagasse is diverted to produce animal feed for feedlot cattle.

(B2) Beef cattle production on feedlot: This system exclusively focuses on the finishing period, with all cattle confined. The animals receive supplementation through an optimized feed that meets all nutritional requirements for their fattening. One of the components of this feed is raw bagasse, a co-product of the biorefinery (B1). The equivalent carcass production in this system - portion of the animal that is used to produce consumable meat - is equal to the production of pasture-fed cattle in A2. The area allocated for confinement is negligible. Thus, the area of the system with integration is half the area without integration, maintaining the production (Figure 1).

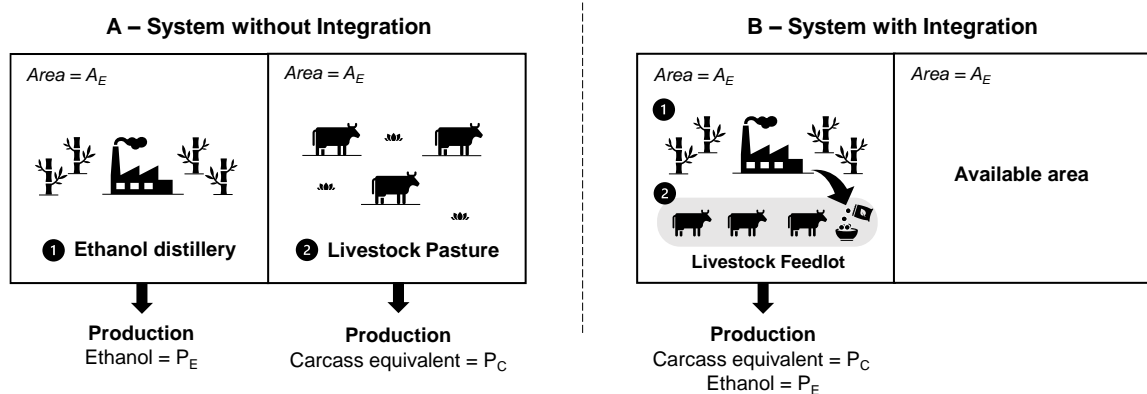


Figure 1. Systems without (A) and with sugarcane-livestock integration (B) considered in this study

2.2 Metamodels construction

Metamodels were built to describe the main characteristics and elements of the previously mentioned systems, using a similar approach to the one used by Bressanin et al. (2021). Using these metamodels, it is feasible to compute economic parameters, including operational costs (OPEX), investment costs (CAPEX), and revenues.

From these parameters, it is then possible to calculate profitability indicators such as the net present value relative to investment (NPV/CAPEX) and the internal rate of return (IRR).

2.2.1 Modelling of sugarcane ethanol distillery system and beef cattle production on pasture

Detailed models were employed to generate the metamodells for the sugarcane ethanol distillery system and beef cattle production on pasture. The Virtual Biorefinery (VB) served as the foundation for modelling the agricultural and industrial phases of the biorefinery (Bonomi et al., 2016). The CanaSoft Model (part of the VB platform) was employed to calculate the recovery costs for sugarcane, soybean, and sugarcane straw (Bonomi et al., 2016). In the industrial phase, the commercial process simulator Aspen Plus® was utilized as the basis for the modelling process (Junqueira et al., 2017). For economic analysis, it was considered a vertically integrated system, i.e., sugarcane production and sugarcane straw recovery costs – calculated with CanaSoft – were considered operational costs to the industrial phase. Regarding the pastoral system, detailed models of beef cattle production developed by the Brazilian Agricultural Research Corporation (EMBRAPA) were considered. In this analysis, a prototype farm in São Paulo state, Brazil, was considered.

The factorial design of experiment (2^k) with a Central Composite Circumscribed Design (CCC) was applied to develop these metamodells. Second-degree polynomial regression was employed to construct the metamodells tested at a 95% confidence level. The quality of the fit of the statistical metamodells was assessed using the coefficient of determination (R^2) and Analysis of Variance (ANOVA).

2.2.2 Modelling of beef cattle production on feedlot

In feedlot livestock farming, most operational costs are related to the animal purchase and feed ingredients, which were directly calculated in the modelling. Additional operational costs, including labor, maintenance, and sanitary management, along with investment costs, were estimated utilizing the methodology outlined by Sartorello et al. (2018).

2.2.3 Modelling of CBIOs

CBIOs were estimated using the biofuel's energy-environment efficiency score based on the life cycle analysis methodology applied by the RenovaBio program. Greenhouse gas (GHG) emissions from each phase (agricultural, industrial, distribution, and use) were estimated using the CanaSoft and VB tools, in addition to the RenovaCalc methodology and the GHG Protocol emission factors (ANP, 2020).

2.3 Optimization Methodology

After obtaining the metamodells (Step 1, Figure 2), the NPV/CAPEX of the sugarcane ethanol distillery system was maximized (Step 2, Figure 2). The decision variables were the sugarcane processing capacity, 2 to 10 million tonnes of sugarcane stalk per year (MTC y^{-1}), and the sugarcane straw recovery, 6.74 to 67.4 kilogram, in dry basis, per tonne of sugarcane stalk ($\text{kg}_{\text{db}} \text{TC}^{-1}$). This optimization provided the optimized area for the biorefinery, which served as an input parameter for pasture-fed beef production and ethanol production, representing an equality constraint in the integrated system. Subsequently, the NPV/CAPEX of pasture-fed beef production was also maximized (Step 3, Figure 2). The decision variable was the stocking rate (1 to 4 heads per hectare). This optimization yielded the carcass equivalent quantity, an equality constraint in the integrated system. With the optimized parameters, it was possible to calculate the systems' NPV/CAPEX and IRR without and with integration (Step 4, Figure 2).

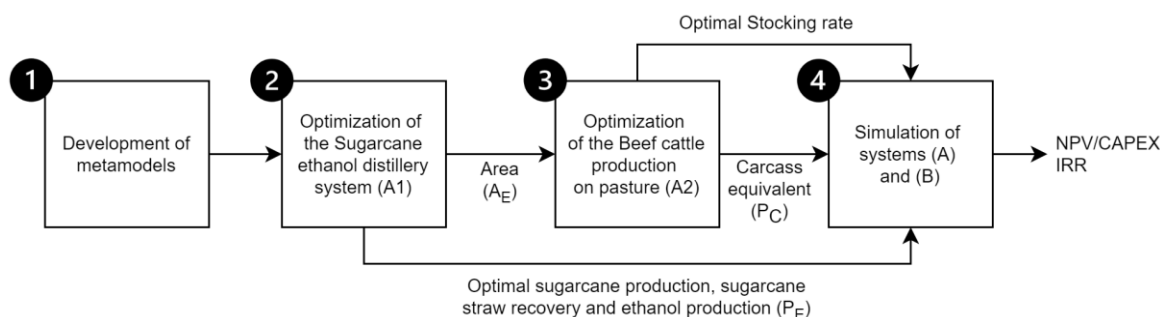


Figure 2. Optimization algorithm, where A = System without integration and B = System with integration

The optimization problem was addressed using the PYOMO library with the IPOPT (Interior Point Optimizer) solver. The optimization process incorporated input parameter values specific to the São Paulo state (Table 1).

The optimal feed formulation considered was 18.9% bagasse, 46.5% corn, 30% DDGS (Dried Distillers Grains with Solubles), 1.3% vegetable oil, 0.5% potassium chloride, 1% calcite, 0.8% urea, and 1% mineral salt. Furthermore, the profitability analysis integrated a 30-year cash flow projection, a minimum rate of attractiveness (MRA) set at 12% per year, straight-line depreciation spanning ten years, a 34% corporate tax rate, and working capital equivalent to 10% of the investment (Bonomi et al., 2016). It was also considered that 1 U.S. dollar is equivalent to 5 Brazilian reais (US\$ 1.00 = R\$ 5.00).

Table 1: Main Inputs parameters considered in the Sugarcane-Livestock Integration – valid for 2019

Inputs	Value	Inputs	Value
Sugarcane agricultural yield (t ha ⁻¹)	80	Feedlot live weight gain (kg head ⁻¹ y ⁻¹)	170
Land rental cost (US\$ ha y ⁻¹)	340	Initial feedlot live weight (kg head ⁻¹)	380
Soybean agricultural yield (t ha ⁻¹)	3.2	Carcass yield (%)	54
Biorefinery operating days (days y ⁻¹)	200	Ethanol price (US\$ L ⁻¹)	0.39
Bagasse diverted to feed or sale (%)	10	Electricity price (US\$ MWh ⁻¹)	42.2
Nitrogen use efficiency (kg animal unit ⁻¹)	90	Soybean price (US\$ (60kg) ⁻¹)	17.6
Initial pasture live weight (kg head ⁻¹)	322	Beef price (US\$ (15kg) ⁻¹)	42.4
Pasture live weight gain (kg head ⁻¹ y ⁻¹)	150	Bagasse price (US\$ kg ⁻¹)	0.024
Feedlot days (day)	100	CBIOs price (US\$ unit ⁻¹)	10

3. Results and discussion

The metamodels developed showed statistical significance, as evidenced by $R^2 > 0.90$. Under the evaluated conditions, optimizing the biorefinery (A1) indicated an optimal sugarcane production of 3.81 MTC y⁻¹, with sugarcane straw recovery reaching 6.74 kg_{d.b.} TC⁻¹ (Table 2). Considering this capacity, the sugarcane production area was estimated at 60 thousand ha, from which 20% is dedicated to reform. Annual ethanol production in the biorefinery was 326.8 million liters y⁻¹. Additionally, the importance of Decarbonization Credits (CBIOs), which contribute approximately 4% to the total revenue of the biorefinery, should be emphasized.

Optimizing pasture (A2) while considering forage mass maintenance resulted in a stocking rate of 4 heads ha⁻¹, aligning with previous studies such as that Boddey et al. (2004). With this stocking rate and the area of 60.14 thousand ha, beef production reached 61.3 thousand tonnes y⁻¹. From a feedlot perspective, this production requires a feedlot capacity of 206,430 heads.

Table 2: Main simulation results for the study case - the decision variables optimized were highlighted

A. System without integration			
A1. Sugarcane ethanol distillery system			
Outputs	Value	Outputs	Value
Sugarcane production (MTC y ⁻¹)	3.81	Soybean cost (US\$ t ⁻¹)	149.08
Sugarcane straw recovery (kg _{d.b.} TC ⁻¹)	6.74	OPEX Inputs (MUS\$ y ⁻¹)	2.28
Sugarcane area (10 ³ ha)	60.14	OPEX Labor (MUS\$ y ⁻¹)	2.86
Ethanol production (ML y ⁻¹)	326.80	OPEX Maintenance (MUS\$ y ⁻¹)	5.91
Electricity production (GWh y ⁻¹)	396.63	OPEX Sugarcane (MUS\$ y ⁻¹)	77.43
Soybean production (10 ³ t y ⁻¹)	32.07	OPEX Straw (MUS\$ y ⁻¹)	0.50
Bagasse production (10 ³ t y ⁻¹)	60.26	OPEX Soybean (MUS\$ y ⁻¹)	4.78
CBIOs (10 ³ unit)	622.7	OPEX Total (MUS\$ y ⁻¹)	93.76
Sugarcane cost (US\$ t ⁻¹)	20.33	CAPEX (MUS\$)	277.58
Straw cost (US\$ t ⁻¹)	19.51	Revenue (MUS\$ y ⁻¹)	172.59
A2. Beef cattle production on pasture			
Outputs	Value	Outputs	Value
Stocking rate (head ha ⁻¹)	4.00	OPEX Mineral supplement (MUS\$ y ⁻¹)	3.39
Nitrogen Dose (kg ha ⁻¹)	277.69	OPEX Sanitary management (MUS\$ y ⁻¹)	3.86
Area (10 ³ ha)	60.14	OPEX Others (MUS\$ y ⁻¹)	0.03
Carcass equivalent (10 ³ t y ⁻¹)	61.31	OPEX Land rent (MUS\$ y ⁻¹)	20.44
OPEX Animal purchase (MUS\$ y ⁻¹)	104.04	OPEX Total (MUS\$ y ⁻¹)	163.45
OPEX Labor (MUS\$ y ⁻¹)	6.81	CAPEX (MUS\$)	50.07
OPEX General Inputs (MUS\$ y ⁻¹)	24.89	Revenue (MUS\$ y ⁻¹)	173.28

B. System with integration*			
B2. Beef cattle production on feedlot			
Outputs	Value	Outputs	Value
Feedlot capacity (10^3 head)	206.43	OPEX Fuel (MUS\$ y^{-1})	0.54
Feed requirement ($\text{kg}_{\text{wet basis}} \text{ head}^{-1} \text{ day}^{-1}$)	12.40	OPEX Labor (MUS\$ y^{-1})	1.35
Bagasse requirement ($10^3 \text{ t } y^{-1}$)	55.86	OPEX Maintenance (MUS\$ y^{-1})	1.89
OPEX Animal feed (MUS\$ y^{-1})	52.61	OPEX Others (MUS\$ y^{-1})	5.91
OPEX Animal purchase (MUS\$ y^{-1})	103.21	OPEX Total (MUS\$ y^{-1})	166.19
OPEX Sanitary management (MUS\$ y^{-1})	0.40	CAPEX (MUS\$)	17.36
OPEX Identification (MUS\$ y^{-1})	0.27	Revenue (MUS\$ y^{-1})	173.28

*The Sugarcane ethanol distillery system B1 has the same results as A1, except for the revenue (165.9 MUS\$ y^{-1}) which is smaller due to the use of part of the bagasse in the feed formulation.

The systems' IRR and NPV/CAPEX exhibited similar behavior in the results, indicating consistency in the data (Table 3). In all cases analyzed, the IRR exceeds the MRA (12%), showing that the investments are profitable under the tested conditions, whether collectively or individually. Furthermore, for the integrated and non-integrated systems, the resulting profitability indicators fall between those of the subsystems forming them. For instance, the IRR of A (19.48) lies between the IRR of A1 (20.39) and A2 (15.38), leaning more towards the biorefinery.

Considering the objective of this study, it is evident that, under the tested conditions, integration proves to be economically attractive, as its indicators surpass those of the non-integrated case. Another inherent benefit of integration is the requirement for a smaller area. While the non-integrated system demands an area of 120 thousand ha, the integrated system needs only half of that, i.e., 60 thousand ha. The available area can be used for other purposes, such as restoring a legal reserve.

Table 3: Profitability results for each system

System	NPV (MUS\$)	CAPEX (MUS\$)	NPV/CAPEX	IRR (%)
A1. Biorefinery	143.73	277.58	0.52	20.39
A2. Livestock Pasture	11.95	50.07	0.24	15.38
A. No integration	155.68	327.65	0.48	19.48
B1. Biorefinery	138.10	277.58	0.50	20.09
B2. Livestock Feedlot	23.70	17.36	1.36	30.08
B. Integration	161.80	294.94	0.55	20.85

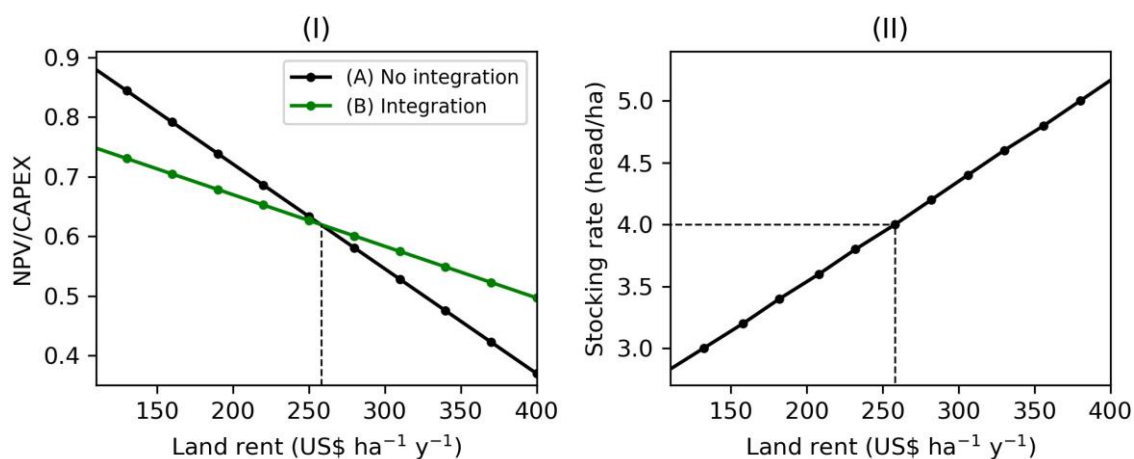


Figure 3. Sensitivity analysis of land rent on NPV/CAPEX (I) and stocking rate (II).

The decision between a system with or without integration heavily depends on the parameters considered in the study. It is observed that NPV/CAPEX is inversely proportional to the land rent for both systems, as expected (Figure 3-I). The lines for systems (A) and (B) intersect at 258 US\$ ha⁻¹, indicating that for lower values, the economically preferable decision is not to integrate sugarcane and livestock production. In contrast, for values

higher than 258 US\$ ha⁻¹, integration becomes economically attractive. This decision value for land rent varies with other parameters, such as stocking rate (Figure 3-II). The 258 US\$.ha⁻¹ value corresponds to a stocking rate of 4 heads ha⁻¹, which was optimized in the study. However, for low stocking rates, integration becomes favorable for even lower land rental values.

A sensitivity analysis was also carried out on ethanol and beef prices. The behavior of the curves was similar to that of land rent (Figure 3.I), but the slope of the curves is closer. This shows that these parameters have less influence on the systems when compared to land rent.

4. Conclusions

In this study, it was possible to model and optimize different systems, considering both integrated and non-integrated configurations between ethanol production and beef cattle farming. The approach developed here is valuable in identifying economically advantageous conditions for integrating biorefinery and livestock farming. Furthermore, the proposed methodology can be applied to investigate other bioenergy production systems, such as corn-based, and explore potential interconnections between livestock and ethanol production systems. Considering the assumptions adopted in this study, it was observed that the system with integration presents better economic results, using half area and maintaining the system's production without integration. It is important to emphasize that the environmental assessment of the integrated system requires attention. Environmental optimization, aiming to minimize emissions, and even a multicriteria approach provide relevant analyses that can be explored in future research.

Acknowledgments

The authors gratefully acknowledge the financial support received from FAPESP (Grant No: 2017/11523-5) and CNPq (Grant No: 140029/2022-2). Additionally, we extend our appreciation to Embrapa Pecuária Sudeste for their invaluable contributions and support in successfully executing this research project.

References

- ANP - Agência Nacional de Petróleo, Gás Natural e Biocombustíveis. Biofuel production – RenovaBio (In portuguese: Produção de Biocombustíveis - RenovaBio. < <https://www.gov.br/anp/pt-br/assuntos/renovabio>> accessed 01.11.2023).
- Boddey R.M., Macedo R., Tarré R.M., Ferreira E., De Oliveira O.C., Rezende C., Cantarutti R.B., Pereira J.M., Alves B.J.R., Urquiaga S., 2004, Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline, *Agriculture, Ecosystems & Environment*, v. 103(2), doi.org/10.1016/j.agee.2003.12.010.
- Bonomi, A., Cavalett, O., Cunha, M.P., Lima, M.A.P., 2016, *Virtual Biorefinery – An Optimization Strategy for Renewable Carbon Valorization*, Springer International Publishing, Switzerland.
- Bressanin, J. M., Geraldo, V. C., Gomes, F. de A. M., Klein, B. C., Chagas, M. F., Watanabe, M. D. B., Bonomi, A., Morais, E. R. de, Cavalett, O., 2021. Multiobjective optimization of economic and environmental performance of Fischer-Tropsch biofuels production integrated to sugarcane biorefineries. *Industrial Crops and Products*, 170.
- Cortez, L., Brito, C. (Org.), Souza, G. (Org.), Cantarella, H. (Org.), Sluys, M. V. (Org.), Maciel, R. (Org.), 2016, *Proálcool 40 Years - Universities and Companies: 40 years of science and technology for Brazilian ethanol* (In Portuguese: Proálcool 40 Anos - Universidades e Empresas: 40 anos de ciência e tecnologia para o etanol brasileiro), 1a. ed. São Paulo: Editora Blucher, 222p.
- Junqueira, T. L., Chagas, M. F., Gouveia, V. L. R., Rezende, M. C. A. F., Watanabe, M. D. B., Jesus, C. D. F., Cavalett, O., Milanez, A. Y., Bonomi, A., 2017, Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons, *Biotechnology for Biofuels* 10(1).
- MAPA. Ministry of Agriculture, Livestock and Supply, 2021, Sectoral plan for adaptation to climate change and low carbon emissions in agriculture with a view to sustainable development (2020-2030): a strategic vision for a new cycle (In portuguese: Plano setorial para adaptação à mudança do clima e baixa emissão de carbono na agropecuária com vistas ao desenvolvimento sustentável (2020-2030): visão estratégica para um novo ciclo), Brasília: MAPA. 1ª ed., 28 p.
- Sartorello, G. L., Bastos, J. P. S. T., Gameiro, A. H., 2018, Development of a calculation model and production cost index for feedlot beef cattle. *Revista Brasileira de Zootecnia*, v. 47.
- Souza, N., Fracarolli, J., Junqueira, T., Chagas, M., Cardoso, T., Watanabe, M., Cavalett, O., Venzke Filho, S., Dale, B., Bonomi, A., Cortez, L., 2019, Sugarcane ethanol and beef cattle integration in Brazil. *BIOMASS & BIOENERGY*, v. 120, p. 448-457. doi.org/10.1016/j.biombioe.2018.12.012.