Energy analysis of sugarcane potential ethanol production from published data: a case study in Campos de Goytacazes – Brazil

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Abstract: Crop rotation with leguminous species in sugarcane cultivation is increasing in the southeastern regions of Brazil. Most of researches done on sugarcane is focused on yield regardless its final product. In the specific case of sugarcane ethanol production, studies rely basically on the economic and sustainable points of view overlooking the energy analysis. This study aimed to evaluate the sugarcane ethanol yield under no-tillage and conventional systems with different green manure treatments on energy efficiency. Sugarcane published dataset was used in the study where different management practices and yield were available. Energy indices from different sources were used to transform all the input into the same unit (MJ). Analysis of energy efficiency was carried out using the indicators: energy balance (EB), energy return over investment (EROI) and Energy Intensity (EI). Analysis of variance and Tukey test at 5% of significance was applied. EB ranged from 148 GJ ha^{-1} to 216 GJ ha^{-1}, with no-tillage over jack beans system presenting the highest values of EB. EI presented that no-tillage systems over spontaneous vegetation presented the highest and statistically different value (1.03 MJ L^{-1}) compared to the other systems (0.69 MJ L^{-1} for both no-tillage over velvet beans and jack beans and 0.66 MJ L^{-1} for sunn hemp). In addition to that, sugarcane yield was statically equal for conventional system and no-tillage over sunn hemp and velvet beans. Energy analysis provided an opportunity to target potential management practices to reduce the consumption of energy to produce the same amount of sugarcane, unable to figure out looking at only the yield (Mg ha^{-1}). Applying energy analysis on the available data, it was shown that sugarcane cultivation with no-tillage and no chemical fertilization with green manure crop rotation is energetically feasible increasing sustainability of sugarcane ethanol production, but it is necessary to highlight the importance to verify the absolute values of EB, EROI and EI indicators along years.

Keywords: conventional system, energy balance, energy input, no-tillage system, sustainability

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1 Introduction

Brazil is the largest producer of sugarcane ethanol in the world. Sugarcane crop covers approximately 10 million hectares of agriculturable fields (Filoso et al., 2015). Adoption of crop rotation with sugarcane is increasing in the southeastern regions of Brazil and the usual crops are nitrogen-fixing leguminous species (*Arachis hypogaea*, *Canavalia ensiformis*, *Crotalaria juncea, Glycine max* and *Mucuna aterrima*) which provides benefits to the sugarcane production (Otto et al., 2016).

Crop rotation with leguminous plants improves nitrogen supply, besides it contributes to reduce soil erosion, nematode and weed control. Consequently, it may increase yield and reduce nitrogen requirement (Otto et al., 2016). Besides crop rotation practices, to improve sustainability of sugarcane production, the adoption of green cane system also resulted in environmental benefits such as reduction of

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greenhouse gases emissions. In this system, sugarcane is mechanically harvested without burning straw (Scala et al., 2006; Bordonal et al., 2013).

Regarding sugarcane sustainability, several studies have focused on the trade-off between yield and its management practices (Cardozo et al., 2018; Duarte and Coelho, 2008) and/or its socio-economic impacts (Du et al., 2019; Prasara-A et al., 2019). But, as concern increases about renewable energy fuels, there are studies aiming to approach the sustainability of biofuels productions from different sources, such as cyanobacteria (Pfannerer et al., 2016), sugarcane (Chagas et al., 2016, Bordonal et al., 2018), waste furniture board (Zhao et al., 2019) and wheat (Safa and Samarasinghe, 2011).

Studies of ethanol production have been conducted mainly by three analysis: economic (Junqueira et al., 2017; Wang et al., 2014), energy (Agostinho and Siche, 2014; Cavalett et al., 2013; Da Vitória and Rodrigues, 2016; Karimi et al., 2008; Veiga et al., 2015) and environmental (Alkimim and Clarke, 2018; Moore et al., 2017; Pereira and Ortega, 2010). Although the importance of sugarcane ethanol, as renewable energy and environmentally more sustainable than fossil fuel (Goldemberg et al., 2008), there is lack of efforts analyzing sugarcane ethanol potential production at the energy point of view applying different crop rotation systems before sugarcane implementation.

Brazilian government initiated to incentivize the use and production of biofuels in Brazil by 1975 with the establishment of the National Alcohol Program (PROALCOOL). To stimulate more biofuels production is Brazil, including sugarcane ethanol production, a program called Decarbonization Credit known as "RENOVABIO" was launched, in which the carbon intensity value from each certified biofuel is determined based on the life cycle analysis (RENOVABIO, 2018).

Due to the importance to produce more, harming the least as possible the environment, the awareness of how fuel concern is being developed and the availability of published data that did not perform energy analysis, there is an opportunity to explore these data to compare energy efficiency. The aim of this study was to evaluate sugarcane potential ethanol yield in scenarios with different crop management practices applying energy analysis from published data focusing to find gaps to increase its sustainability production.

2 Material and methods

2.1 Area of study

The dataset of the sugarcane study-case was based on Duarte and Coelho (2008) who analyzed agronomic parameters of a sugarcane crop under no-tillage and conventional systems (tillage system applying the plow and harrow) with different treatments of green manure crops and chemical fertilizations in a field experiment at Campos de Goytacazes (21º44'47''S and 41º18'24''W), Rio de Janeiro, Brazil.

The experiment was conducted with sugarcane conventional and no-tillage systems soils classified as Cambisols with appropriate drainage and silty clay loam texture (38%, 52% and 10% of clay, silt and sandy contents, respectively) from March of 2004 to July 2005. During the period of 1994 and 2004, the area did not receive fertilizer application at the planting and covering periods of sugarcane.

2.2 Sugarcane cultivation and management practices

Four months before sugarcane planting, it was applied 0.75 t ha^{-1} of limestone (relative power of total neutralization of 80%) and 0.23 t ha^{-1} of gypsum. After that, it was planted the following green manures: 25 kg ha^{-1} of *Crotalaria juncea* (sunn hemp), 100 kg ha^{-1} of *Canavalia ensifomis* (jack beans) and 60 kg ha^{-1} of *Mucuna aterrima* (velvet bean).

The treatments were distinguished by system and fertilizer application. The systems were: (A) no-tillage over sunn hemp, (B) no tillage over jack beans, (C) no tillage over velvet beans, and (D) conventional over spontaneous vegetation. Fertilizer application was performed using (A) no fertilizer application and (B) 444 and 133 kg ha^{-1} of single superphosphate and potassium chloride, respectively. Therefore, the experiment had a factorial distribution of 4 ×

2.

Each treatment was conducted with sugarcane SP80-1842 variety under an experimental area of 121 m^2 disposed by eight sugarcane rows spaced by 1.3 m. It was conducted a weed control after 15 days of sugarcane planting at all the treatments. It was applied, during the morning from 6 am to 7 am, pre-and post-emergent herbicides at the rate of 2.0 kg ha^{-1} of herbicide 1 (Diuron and Hexazinone) and 2.4 kg ha^{-1} of herbicide 2 (Monosodium Methanearsonate).

Sugarcane yield data were collected at the maturity stage (July 2005) and the samples were taken from the two middle rows of the experimental unit. The material flow and the diagram of sugarcane crop production were elaborated based on the reference material and the energy indices for agricultural inputs and outputs for sugarcane production were composed by a sort of important references.

There are several differences from point estimates regarding energy equivalent since technology and methods of estimation present some differences. But, in this study, the energy coefficients were carefully selected to attend the closest as possible to our regional scenario. Therefore, we attempted to select the most recent energy studies related to sugarcane ethanol production and its crop management.

2.3 Energy analysis

The energy flow analysis was carried out using the indicators i) energy balance (EB, Equation 1, GJ ha^{-1}), ii) energy input flow (EIF, GJ ha^{-1}) , iii) energy output flow (EOF, GJ ha^{-1}), iv) energy return over investment (EROI, Equation 2, GJ GJ^{-1}) and energy intensity (EI, Equation 3, MJ L^{-1}) described by Nunes et al. (2010) and Romanelli and Milan (2010).

$$EB = EOF - EIF \tag{1}$$

where, *EB*, *EOF* and *EIF* are, respectively, energy balance (GJ ha^{-1}), energy output flow (GJ ha^{-1}) and energy input flow (GJ ha^{-1}).

$$EROI = EB/EIF^{1} \tag{2}$$

where, *EROI*, *EB* and *EIF* are, respectively, energy return over investment (GJ GJ^{-1}), energy balance (GJ ha^{-1}) and energy input flow (GJ ha^{-1}).

$$EI = 1000 \times EIF/YIELD \tag{3}$$

where, *EI*, *EIF* and *YIELD* are, respectively, energy intensity (MJ L^{-1}), energy input flow (GJ ha^{-1}) and ethanol potential yield (L ha^{-1}).

It was considered only parameters that were different among systems to determine *EB*, *EROI* and *EI*. Labor was not accounted because that information was not clearly shown in the reference material, and generally it represents minute values for mechanized systems, for example, 0.07 GJ ha^{-1} in sugarcane system (Veiga et al., 2015).

2.4 Statistical analysis

Analysis of variance (ANOVA) was performed with the average values found in the reference material and the energy parameters calculated at a 5% of probability. And also, it was applied Tukey test at 5% of significance, in the cases where *p*-value was lower than 0.05 in ANOVA. All the statistical analyses were performed on R environment (R Core Team, 2019).

3 Results and discussion

Figure 1 presents a general diagram of the sugarcane production system independently on the cultivation system. It is important to note that in this diagram the seeds and stalk refers to the green manure crops and sugarcane stalks, respectively. Yield is the parameter to be evaluated as consequence of the different managements within sugarcane cultivation. The main energy indices in agricultural inputs and outputs used in this study are shown at the Table 1. Note that not all the farm energy inputs were used in this study because our focus was to make a comparison between different inputs used among crop management.

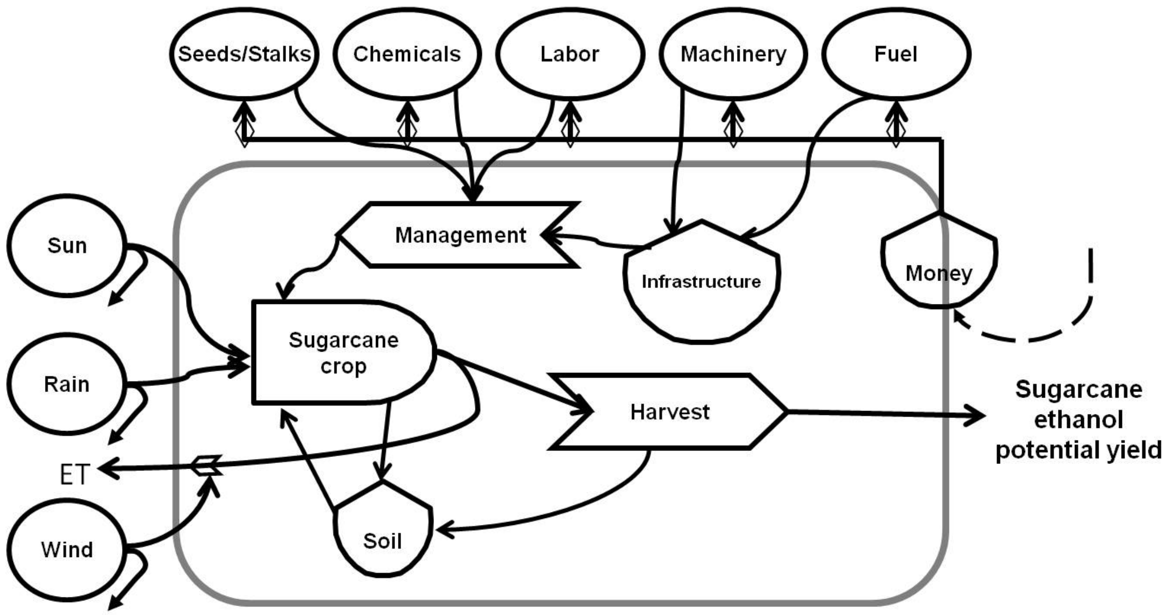

Figure 1 Sugarcane production system

Table 1 Embodied energy in agricultural inputs and outputs

Item	Unit	Energy Index (MJ unit^{-1})	Reference
Plowing	ha	1420.43	Fernandes et al. (2008)
Harrowing	ha	573.80	Fernandes et al. (2008)
Scarification	ha	749.09	Fernandes et al. (2008)
Labor	h	2.20	Pimentel (1980)
Limestone	kg	1.70	Pellizzi (1992)
Single Superphosphate	kg	25.20	Aguilera et al. (2015)
Potassium chloride	kg	12.40	Ramírez and Worrell (2006)
Sunn hemp seeds	kg	23.22	Dutta et al. (2014)
Jack bean seeds	kg	15.46	Olalekan and Bosede (2010)
Velvet bean seeds	kg	19.50	Vadivel and Janardhanan (2000)
Herbicide	L	454.20	Fluck and Baird (1982)
Pesticide	L	184.70	Pimentel (1980)
Ethanol	L	19.83	Pereira and Ortega (2010)

Material flows of the sugarcane crop system (Table 2) allow one to compare the effects on material requirement from the distinct cropping systems. Components with differences among systems were plowing, harrowing, chemical fertilization and green manure crop planting.

Table 2 Material flow of the sugarcane crop system

	Material	Unit	No-tillage system						Conventional system	
			CF[a]			NCF[b]			CF[a]	NCF[b]
			I	II	III	I	II	III	IV	IV
			Frequency							
A	**Machinery**									
A.1	Plowing	times	0	0	0	0	0	0	1	1
A.2	Harrowing	times	0	0	0	0	0	0	2	2
A.3	Grooving	times	1	1	1	1	1	1	1	1
A.4	Scarification	times	1	1	1	1	1	1	1	1
B	**Labor**									
B.1	Green manure seedling	times	1	1	1	1	1	1	0	0
B.2	Sugarcane planting	times	1	1	1	1	1	1	1	1
B.3	Fertilizer application	times	1	1	1	0	0	0	1	0
B.4	Herbicide application	times	1	1	1	1	1	1	1	1

C	Inputs	Unit ha^{-1}								
C.1	Limestone	kg	750	750	750	750	750	750	750	750
C.2	Gypsum	kg	230	230	230	230	230	230	230	230
C.3	Single Superphosphate	kg	444	444	444	0	0	0	444	0
C.4	Potassium chloride	kg	133	133	133	0	0	0	133	0
C.5	Sunn hemp seeds	kg	25	0	0	25	0	0	0	0
C.6	Jack bean seeds	kg	0	100	0	0	100	0	0	0
C.7	Velvet bean seeds	kg	0	0	60	0	0	60	0	0
C.7	Sugarcane steam	Mg	15	15	15	15	15	15	15	15
C.8	Herbicide 1[c]	kg	2	2	2	2	2	2	2	2
C.9	Herbicide 2[d]	kg	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
C.10	Pesticide[e]	L	200	200	200	200	200	200	200	200
D	**Outputs**									
D.1	Ethanol potential yield	L ha^{-1}	10,68	11,61	11,03	9,81	11,02	10,86	9,14	6,67

Note: CF[a]: Chemical fertilization; NCF[b]: No-chemical fertilization; Herbicide 1[c]: Diuron+hexazinone; Herbicide 2[d]: Monosodium methanearsonate; Pesticide[e]: Alkyl phenol polyglycol ether (2%) spreader adhesive.

Table 3 Material flow and energy indicators of the main different components between sugarcane cultivation systems

Material flow	No-tillage system						Conventional system	
	CF[a]			NCF[b]			CF[a]	NCF[b]
	I	II	III	I	II	III	IV	IV
Inputs	GJ ha^{-1}							
Plowing	0.00	0.00	0.00	0.00	0.00	0.00	1.42	1.42
Harrowing	0.00	0.00	0.00	0.00	0.00	0.00	1.15	1.15
Single superphosphate	11.19	11.19	11.19	0.00	0.00	0.00	11.19	0.00
Potassium chloride	1.65	1.65	1.65	0.00	0.00	0.00	1.65	0.00
Sunn hemp seeds	0.58	0.00	0.00	0.58	0.00	0.00	0.00	0.00
Jack bean seeds	0.00	1.55	0.00	0.00	1.55	0.00	0.00	0.00
Velvet bean seeds	0.00	0.00	1.17	0.00	0.00	1.17	0.00	0.00
Outputs	GJ ha^{-1}							
Ethanol potential yield	211.82	230.31	218.63	194.58	218.47	215.26	181.34	132.34
Energy indicators	GJ ha^{-1}							
EIF[c]	13.42	14.38	14.01	0.58	1.55	1.17	15.41	2.57
EOF[d]	211.82	230.31	218.63	194.58	218.47	215.26	181.34	132.34
EB[e]	198.40	215.92	204.62	193.99	216.92	214.09	165.93	129.78
EB[e] (MJ L^{-1})	18.57	18.59	18.56	19.77	19.69	19.72	18.14	19.45
EROI[f] (GJ GJ^{-1})	14.79	15.01	14.61	334.19	140.31	182.98	10.77	50.54
EI[g] (MJ L^{-1})	1.26	1.24	1.27	0.06	0.14	0.11	1.68	0.38

Note: CF[a]: Chemical fertilization; NCF[b]: No-chemical fertilization; EIF[c]: Energy input flow; EOF[d]: Energy output flow; EB[e]: energy balance; EROI[f]: energy return over investment; EI[g]: energy intensity.

Looking at the energy indicators, it is possible to visualize that energy input achieved the highest values under the systems with chemical fertilizer application, but the energy output did not present the same trends. The energy output values presented values with a range from 201.2 GJ ha^{-1} to 255.5 GJ ha^{-1} under the conventional and no-tillage systems excepting for the treatment with no chemical fertilization of the conventional system which presented an EOF of 146.8 GJ ha^{-1}. The no-tillage system obtained the highest values of EB independently the green manure crop and the application of chemical fertilizers. It is also notable that average EB (19.06 MJ L^{-1}) in this study presented value different from other studies such as Macedo et al. (2008), Wang et al. (2012), Manochio et al. (2017) and Mekonnen et al. (2018), which found the values of 22.6, 16.4, 21.7 and 17.7 MJ L^{-1}, respectively. Different values of EB are expected to be found on different cultivation system and input data (Table 3).

ANOVA results for the calculated energy parameters and sugarcane yield show that only EIF and EI had a significant difference for system and fertilizer treatments. EB and yield were significant different at a 5% only for the system (Appendix A).

Looking at Table 4, it can be noticed that treatments with chemical fertilizer had significant higher energy input flow values than non-chemical treatment which can be explained by the use of chemical that accounts the most for energy input. Regarding to the system, it is shown that conventional system had the highest EIF values followed by no-tillage over jack beans, velvet beans and sunn hemp. Chagas et al. (2016) found that the scenarios of sugarcane production with crop rotation (reduced tillage) especially with sunn hemp presented lower use of nitrogen fertilization and agrochemicals implying to a lower energy input compared to use of tillage system, but there was a trade-off between energy input and yield. In both cases, sunn hemp presented the lowest energy input, but sugarcane crop production was penalized with lower yield. Hence, in this paper, yield was statistically equal from conventional sugarcane production over spontaneous system and no-tillage over sunn hemp indicating that, the latter used less energy to produce the same amount of mass.

Statistical analysis (Tukey test) was performed for EB and yield comparison within systems (Table 4), respectively. It is worth noting that despite both tables presented Tukey grouping classification similar despite the difference found for energy input flow. These results indicate that only no-tillage system over jack beans presented the best results for EB and yield compared to the conventional.

Regarding the EI indicators, the analyses indicate that no-tillage system under no chemical fertilization with sunn hemp, jack bean or velvet bean as green manure crop performed the best compared to the conventional system over spontaneous vegetation at the energy point of view (Table 4), result expected since the use of leguminous crop reduce the need for nitrogen chemical sources (Yang et al., 2013) .Additionally, it is clearly shown that non-chemical treatment presented the best performance on energy intensity with the lowest value and different ($p < 0.05$) from the chemical treatments.

If we consider only sugarcane yield production as a result of its management practices in a sustainability scenario where it is known that main final products from sugarcane are ethanol and sugar, we are wrongly analyzing what really matters. And in this case, we have to look at the ethanol potential production at the energy point of view. Data from Duarte and Coelho (2008) show that sugarcane yields are not statically different from conventional and no-tillage over sunn hemp nor velvet beans (Table 4) and it does not show any opportunity to find ways to improve its sustainability production. But considering EI, it shows that there is a gap to improve sugarcane yield production in a more sustainably. Following energy consumption in agricultural productions can help to understand factors that influence the use of energy and indicate potential targets to reduce energy consumption (Safa and Samarasinghe, 2011).

Table 4 Tukey test for energy input flow (GJ ha^{-1}), energy intensity (MJ L^{-1}), energy balance (GJ ha^{-1}) and sugarcane yield (Mg ha^{-1}) comparison within system and/or fertilizer treatments

Variable response	System	Average	Fertilizer	Average
EIF[1] (GJ ha^{-1})	Conventional over Spontaneous Vegetation	8.99 a	Chemical	14.31 A
	No-tillage over Jack Beans	7.97 b		
	No-tillage over Velvet Beans	7.59 c	Non-Chemical	1.47 B
	No-tillage over Sunn Hemp	7.00 d		
EI[2] (MJ L^{-1})	Conventional over Spontaneous Vegetation	1.03 a	Chemical	1.36 A
	No-tillage over Velvet Beans	0.69 b		
	No-tillage over Jack Beans	0.69 b	Non-Chemical	0.17 B
	No-tillage over Sunn Hemp	0.66 b		
EB[3] (GJ ha^{-1})	No-tillage over Jack Beans	216.42 a	----------	----------

	No-tillage over Velvet Beans	209.36 ab	----------	----------
	No-tillage over Sunn Hemp	196.20 ab	----------	----------
	Conventional over Spontaneous Vegetation	147.86 b	----------	----------
YIELD[4] (Mg ha^{-1})	No-tillage over Jack Beans	141.28 a	----------	----------
	No-tillage over Velvet Beans	134.40 ab	----------	----------
	No-tillage over Sunn Hemp	131.91 ab	----------	----------
	Conventional over Spontaneous Vegetation	99.01 b	----------	----------

Note: EIF[1]: energy input flow, EI[2]: energy intensity, EB[3]: energy balance, YIELD[6]: sugarcane yield.

Average values followed by lowercase letters are compared between system treatment and uppercase letters between fertilizer treatments by Tukey test at 5% of significance. Equal letters followed by the same lowercase letters or uppercase letters do not differ significantly at the level of 5% probability within their treatment.

These results were found for the first year of sugarcane harvest which might be different for other years, mainly because energy parameters are directly related to yield which decreases along years. For example, Ferreira et al. (2015) found different sugarcane yield comparing first, second and third cycle of sugarcane crops.

4 Conclusion

The energy analysis in this study provided a preview of the potential to cultivate sugarcane crops aiming the ethanol production under no-tillage systems without chemical fertilization, applying crop rotation, reducing the energy input and producing the same yield with velvet beans and sunn hemp. In addition to that, the energy analysis proved to be a good indicator of sugarcane ethanol potential yield regarding energy sustainability. Despite these findings, it is necessary to highlight the importance to verify the absolute values of EB, EROI and EI indicators which may not represent the reality.

References

Agostinho, F., and R. Siche. 2014. Hidden costs of a typical embodied energy analysis: Brazilian sugarcane\nethanol as a case study. *Biomass Bioenergy*, 71: 69–83.

Aguilera, E., G. I. Guzmán, J. Infante-amate, R. García-ruiz, A. Herrera, and I. Villa. 2015. Embodied energy in agricultural inputs. incorporating a historical perspective. *Sociedad Española de Historia Agraria*. Available at: https://ideas.repec.org/p/seh/wpaper/1507.html. Accessed on 4 August 2019.

Alkimim, A., and K. C. Clarke. 2018. Land use change and the carbon debt for sugarcane ethanol production in Brazil. *Land Use Policy*. 72(mar): 65–73.

Bordonal, R. de O., E. B. De Figueiredo, D. A. Aguiar, M. Adami, B. F. T. Rudorff, and N. L. Scale. 2013. Greenhouse gas mitigation potential from green harvested sugarcane scenarios in São Paulo State, Brazil. *Biomass and Bioenergy*, 59(dec): 195-207.

Bordonal, R. de O., J. L. N. Carvalho, R. Lal, E. B. De Figueiredo, B. G. De Oliveira, N. L. Scala. 2018. Sustainability of sugarcane production in Brazil. A review. *Agronomy for Sustainable Development*, 38(2): 13.

Cardozo, N. P., R. de O. Bordonal, and N. L. Scala. 2018. Sustainable intensification of sugarcane production under irrigation systems, considering climate interactions and agricultural efficiency. *Journal of Cleaner Production*, 204(dec): 861-871.

Cavalett, O., M. F. Chagas, J. E. A. Seabra, and A. Bonomi. 2013. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. *International Journal of Life Cycle Assessment*, 18(3): 647-658.

Chagas, M. F., R. de O. Bordonal, O. Cavalett, J. L. N. Carvalho, A. Bonomi, and N. L. Scala. 2016. Environmental and economic impacts of different sugarcane production systems in the ethanol biorefinery. *Biofuels Bioproducts and Biorefining*, 10(1): 89-106.

Da Vitória, E. L., and J. P. Rodrigues. 2016. Emergy efficiency analysis of sugarcane as a raw material for ethanol production. *Revista Ciencia Agronomica* 47(4): 616–623.

Du, C., C. Ugaya, F. Freire, L. C. Dias, and R. Clift. 2019. Enriching the results of screening social life cycle assessment using content analysis: a case study of sugarcane in Brazil. *International Journal of Life Cycle Assessment*, 24: 781-793.

Duarte, J. B., and F. C. Coelho. 2008. A cana-de-açúcar em sistema de plantio direto comparado ao sistema convencional com e sem adubação. *Revista Brasileira de Engenharia Agrícola e Ambiental - Agriambi*, 12(6): 576-583.

Dutta, R., U. Sarkar, and A. Mukherjee. 2014. Extraction of oil from Crotalaria Juncea seeds in a modified Soxhlet apparatus: Physical and chemical characterization of a prospective bio-fuel. *Fuel*, 116: 794–802.

Fernandes, H. C., J. C. M. Da Silveira, and P. C. N. Rinaldi. 2008. Avaliação do custo energético de diferentes operações agrícolas mecanizadas. *Ciência E Agrotecnologia*, 32(5): 1582-1587.

Ferreira, D. A., H. C. J. Franco, R. Otto, A. C. Vitti, C. Fortes, C. E. Faroni, A. L. Garside, and P. C. O. Trivelin. 2015. Contribution of N from green harvest residues for sugarcane nutrition in Brazil. *Bioenergy*, 8(5): 859-866.

Filoso, S., J. B. Do Carmo, S. F. Mardegan, S. R. M. Lins, T. F. Gomes, and L. A. Martinelli. 2015. Reassessing the environmental impacts of sugarcane ethanol production in Brazil to help meet sustainability goals. *Renewable and Sustainable Energy Reviews*, 52: 1847–1856.

Fluck, R. C., and C. D. Baird. 1982. *Agricultural Energetics*. Gainesville: University of Florida, Agricultural Engineering Department and Institute de Food and Agricultural Sciences.

Goldemberg, J., S. T. Coelho, and P. Guardabassi. 2008. The sustainability of ethanol production from sugarcane. *Energy Policy*, 36(6): 2086-2097.

Junqueira, T. L., M. F. Chagas, V. L. R. Gouveia, M. C. A. F. Rezende, M. D. B. Watanabe, C. D. F. Jesus, O. Cavalett, A. Y. Milanez, and A. Bonomi. 2017. Techno-economic analysis and climate change impacts of sugarcane biorefineries considering different time horizons. *Biotechnol. Biofuels*, 10(1): 50.

Karimi, M., A. R. Pour, A. Tabatabaeefar, and A. Borghei. 2008. Energy analysis of sugarcane production in plant farms: a case study in Debel Khazai Agro-industry in Iran. *American-Eurasian Journal of Agricultural and Environmental Sciences*, 4(2): 165–171.

Macedo, I. C., J. E. A. Seabra, and J. E. A. R. Silva. 2008. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass Bioenergy*, 32: 582−595.

Manochio, C., B. R. Andrade, R. P. Rodriguez, and B. S. Moraes. 2017. Ethanol from biomass: A comparative overview. *Renewable and Sustainable Energy Reviews*, 80: 743-755.

Mekonnen, M. M., T. L. Romanelli, C. Ray, A. Y. Hoekstra, A. J. Liska, and C. M. U. Neale. 2018. Water, energy, and carbon footprints of bioethanol from the U.S. and Brazil. *Environmental Science and Technology*, 52(24): 14508-14518.

Moore, C. C. S., A. R. Nogueira, and L. Kulay. 2017. Environmental and energy assessment of the substitution of chemical fertilizers for industrial wastes of ethanol production in sugarcane cultivation in Brazil. *The International Journal of Life Cycle Assessment*, 22(mar): 628–643.

Nunes, A., T. L. Romanelli, and K. Reichardt. 2010. Energy flow in castor bean (Ricinus communis L .) production systems. *Scientia Agricola*, 67(6): 737-742

Olalekan, A. J., and B. F. Bosede. 2010. Comparative study on chemical composition and functional properties of three Nigerian legumes (Jack beans, Pigmeon pea and Cowpea). *Journal of Emerging Trends in Engineering and Applied Sciences*, 1(1): 89–95.

Otto, R., S. A. Q. Castro, E. Mariano, S. G. Q. Castro, H. C. J. Franco, and P. C. O. Trivelin. 2016. Nitrogen use efficiency for sugarcane-biofuel production: what is next? *BioEnergy Research*, 9(4): 1272–1289.

Pellizzi, G. 1992. Use of energy and labour in Italian agriculture. *Journal of Agricultural Engineering Research*, 52(may-aug): 111-119.

Pereira, C. L. F., and E. Ortega. 2010. Sustainability assessment of large-scale ethanol production from sugarcane. *Journal of Cleaner Production*, 18(1): 77–82.

Pfannerer, F., K. Krennhuber, A. Jager, and H. Kahr. 2016. New constructs for ethanol production via cyanobacteria. *Agronomy Research*, 14(1): 174-180.

Pimentel, D. 1980. *Handbook of Energy Utilization in Agriculture.* Boca Raton: CRC Press

Prasara-A, J., S. H. Gheewala, T. Silalertruksa, P. Pongpat, and W. Sawaengsak. 2019. Environmental and social life cycle assessment to enhance sustainability of sugarcane-based products in Thailand. *Clean Technologies and Environmental Policy*, 21(7): 1447-1458.

R Core Team. 2019. R: A language and environment for statistical computing (Version 3.6.0). Vienna, Austria: R Foundation for Statistical Computing.

Ramírez, C. A., and E. Worrell. 2006. Feeding fossil fuels to the soil: an analysis of energy embedded and technological learning in the fertilizer industry. *Resources, Conservation and Recycling*, 46(2006): 75–93.

RENOVABIO. 2018. Crédito de Descarbonização (CBIO). Available at: https://www.renovabio.org/cbios/. Accessed on 4 August 2019.

Romanelli, T. L., and M. Milan. 2010. Energy performance of a production system of eucalyptus. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 14(8): 896-903.

Safa, M., and S. Samarasinghe. 2011. Determination and modelling of energy consumption in wheat production using neural networks: "a case study in Canterbury province, New Zealand". *Energy*, 36: 5140-5147.

Scala, N. L., D. Bolonhezi, and G. T. Pereira. 2006. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. *Soil and Tillage Research*, 91(1-2): 244-248.

Vadivel, V., and K. Janardhanan. 2000. Nutritional and anti-nutritional composition of velvet bean: an under-utilized food legume in South India. *International Journal of Food Sciences and Nutrition*, 51(4): 279-287.

Veiga, J. P. S., T. L. Romanelli, L. M. Gimenez, P. Busato, and M. Milan. 2015. Energy embodiment in Brazilian agriculture: an overview of 23 crops. *Scientia Agricola*, 72(6): 471–477.

Wang, L., R. Quiceno, C. Price, R. Malpas, and J. Woods. 2014. Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward. *Renewable and Sustainable Energy Reviews*, 40(dec): 571-582.

Wang, M., J. Han, J. B. Dunn, H. Cai, and A. Elgowainy. 2012. Well-towheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environmental Research Letters*, 7(4): 45905-45917.

Yang, W., Z. Li, J. Wang, P. Wu, and Y. Zhang. 2013. Crop yield, nitrogen acquisition and sugarcane quality as affected by interspecific competition and nitrogen application. *Field Crops Research*, 146: 44-50.

Zhao, J., D. Tian, F. Shen, J. Hu, Y. Zeng, and C. Huang. 2019. Valorizing waste lignocellulose-based furniture boards by phosphoric acid and hydrogen peroxide (Php) pretreatment for bioethanol production and high-value ligin recovery. *Sustainability*, 11(21): 6175.

APPENDIX A

Table 5 Analysis of variance for energy input flow, energy output flow, energy balance, energy return over investment, energy intensity and sugarcane yield as responses to fertilizer application and different green manures

Variable response	Source	DF	SS	MS	F	P-value
EIF[1]	System	3	4.2	1.4	111876	< 0.001***
	Fertilizer	1	329.6	329.6	26368225	< 0.001***
	Residuals	3	0	0	----------	----------
EOF[2]	System	3	5509	1836.4	9.249	0.05
	Fertilizer	1	829	829.3	4.177	0.134
	Residuals	3	596	198.5	----------	----------
EB[3]	System	3	5726	1908.7	9.619	0.048*
	Fertilizer	1	113	113.2	0.57	0.505
	Residuals	3	595	198.4	----------	----------
EROI[4]	System	3	21547	7182	1.049	0.485
	Fertilizer	1	53275	53275	7.778	0.069
	Residuals	3	20548	6849	----------	----------
EI[5]	System	3	0.185	0.06	17.45	0.021*
	Fertilizer	1	2.8322	2.83	801.57	< 0.001***
	Residuals	3	0.0106	0.01	----------	----------
YIELD[6]	System	3	2131.7	710.6	12.406	0.034*
	Fertilizer	1	244.2	244.2	4.263	0.131
	Residuals	3	171.8	57.3	----------	----------

Note: EIF[1]: energy input flow, EOF[2]: energy output flow, EB[3]: energy balance, EROI[4]: energy return over invest- ment, EI[5]: energy intensity, YIELD[6]: sugarcane yield, DF: degrees of freedom, SS: sum of squares, MS: mean square error.

“*”, “**” and “***” significant at 0.05, 0.01 and 0.001 probability levels by F test, respectively.