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Revista Ciência Agronômica, vol. 47, núm. 4, octubre-diciembre, 2016, pp. 616-623
Universidade Federal do Ceará
Ceará, Brasil

Revista Ciência Agronômica, v. 47, n. 4, p. 616-623, out-dez, 2016
Centro de Ciências Agrárias - Universidade Federal do Ceará, Fortaleza, CE
www.ccarevista.ufc.br

Artigo Científico
ISSN 1806-6690

Emergy efficiency analysis of sugarcane as a raw material for ethanol production[1]

Análise da eficiência emergética da cana de açúcar como matéria prima na produção de etanol

Edney Leandro da Vitória[2]* and Joice Paraguassú Rodrigues[2]

ABSTRACT - In recent years, the expansion of sugarcane cultivation in Brazil and its growing importance in the Brazilian economy have been driven by a sharp increase in fuel alcohol production. This increase in fuel alcohol production was accompanied by increasing interest regarding the impacts of fuel crops in Brazil. In this study, regions of sugarcane expansion into deforested areas in the Atlantic Forest were studied by applying the emergy theory and indices. Environmental and economic inputs and the sustainability of the sugarcane production system were evaluated with the emergy method. The transformity (TR) was equal to 1.78E+11 seJ kg^{-1}, the yield rate (EYR) was equal to 1.30, the investment rate was equal to 3.29, the environmental load rate was equal to 4.33, the renewability rate was equal to 18.77, and the exchange rate was equal to 1.09. The emergy indices of corn, cassava, wheat, and sugarcane (as raw materials for ethanol production) were used. In Brazil, sugarcane production for ethanol production was more emergetically sustainable based on the analysed emergy indices.

Key words: Sustainability. Environment. Ethanol production.

RESUMO - A expansão da cana de açúcar no Brasil nos últimos anos e sua crescente importância na economia brasileira a partir do início do ano 2000, impulsionada pelo aumento vertiginoso da produção de álcool combustível, trás à tona o interesse em estudar os impactos dessa cultura no território brasileiro. A partir desta premissa, usou-se como campo de estudo as regiões de expansão da cana de açúcar em áreas desmatadas de mata atlântica. A teoria e os índices emergéticos foram aplicados. As entradas ambientais e econômicas e de sustentabilidade do sistema de produção da cana de açúcar foram avaliados usando a metodologia emergética. A transformidade (TR) foi igual a 1,78E+11 Sej kg^{-1}, a taxa de rendimento (EYR) igual 1,30, a taxa de investimento de 3,29, a taxa de carga ambiental foi igual a 4,33, a taxa de renovabilidade de 18,77 e a taxa de intercâmbio de 1,09. Os índices emergéticos de quatro culturas usadas como matéria prima para produção de etanol foram comparados, o milho, a mandioca, o trigo e a cana de açúcar. De acordo com os índices a produção de cana de açúcar como matéria prima na produção de etanol no Brasil é mais sustentável emergeticamente considerando os índices emergéticos analisados.

Palavras-chave: Sustentabilidade. Meio ambiente. Produção de etanol.

*Autor para correspondência
DOI: 10.5935/1806-6690.20160074
[1]Recebido para publicação em 22/10/2013; aprovado em 16/03/2016
Financiamento da Fundação de Amparo a Pesquisa do Espírito Santo/FAPES
[2]Departamento de Ciências Agrárias e Biológicas, Universidade Federal do Espírito Santo/DCAB/UFES, Rod. BR 101 km 60, Campus São Mateus, São Mateus-ES, Brasil, 29.932-540, edney.vitoria@ufes.br, joice_820@hotmail.com

INTRODUCTION

The increasing attention given to oil shortages and environmental deterioration has resulted in technological research and development for the use of biomass-derived fuels, which are called biofuels. Biofuels can positively affect social and economic development. For example, biofuels can reduce poverty, create jobs, reduce dependency on imported oil, and increase access to modern energy services (SCHEFFRAN, 2010).

According to Kaygusuz (2012), the United States is the world's leader in generating energy from biomass. As the second largest energy source in 2010, biomass accounted for 31.1% of Brazil's energy matrix; the dominant energy source was oil and its derivatives. In addition, biomass energy production was also the second largest domestic electric energy source, accounting for 3.7% of the total energy supply. In this case, the dominant energy source was hydroelectricity, which was responsible for producing 77.4% of the total supply (ABRAMOVAY, 2010).

Moreover, Brazil is the second largest international ethanol producer, most of which is made from sugarcane. According to the Brazilian National Energy Balance, ethanol production in Brazil reached 11,900 Mtoe (tons of oil equivalent in millions) in 2013, up from 13,019 Mtoe in 2014, an increase of 9.40% (LIMA *et al*., 2015).

Several methods can be used to evaluate fuel ethanol, including energy analysis (LENG *et al*., 2008; LIMA JÚNIOR *et al*., 2014; NGUYEN; GHEEWALA; GARIVAIT, 2008; SUIRAN; JING, 2009), economic analysis (SUIRAN; JING, 2008; ZHANG *et al*., 2003), environmental assessment (CAVALETT *et al.*, 2012) and exergetic assessment (MOYA *et al*., 2013). However, the production of biomass that is used to produce ethanol should be properly evaluated regarding yield, sustainability, and environmental impact as a function of planting (YANG *et al*., 2010). No generally excepted evaluation method exists for assessing a system's sustainability. Each of the previously mentioned methods has advantages that can help define a system's sustainability from a particular perspective.

Odum proposed the emergy method in 1983. To understand this method, the main concepts encompassed by it must be understood, including emergy, transformity, systemic diagrams, emergy analysis tables, and emergy indices. In 1967, Odum and Nilsson (1996) began using the term "embodied energy" to denote the calories (or Joules) of one energy type that are needed to produce another energy type. However, "embodied energy" has been used by other researchers to define different concepts that were based on different rationales and calculations. Since then, many scientific groups worldwide have used emergy to represent the "energy memory" of a certain type of energy that is used to make another type of energy (CHEN *et al*., 2011).

Sugarcane is the main source of raw materials for ethanol production in Brazil. In this study, multiple research possibilities exist, including the following: an analysis that considers the entire sugarcane production chain, including the industrial stage; a study on the economic, financial, social, and emergetic impacts of ethanol production on deforested areas in the Atlantic Forest biome; or a study that considers alternatives for ethanol production and/or biofuels. Moreover periodic assessments of the environmental impacts of ethanol production, like this one, are needed to ensure that sustainable guidelines are implemented as production expands and evolves (CARVALHO; BATELLO, 2009; FILOSO *et al*., 2015).

This article evaluates the sugarcane production systems for ethanol production in deforested areas of the Brazilian Atlantic Forest with emergy analysis.

MATERIAL AND METHODS

We assessed three sugarcane plantations in the semiarid region of Brazilian between 2010 and 2011. Specifically, these plantations occurred in the deforested areas of the Atlantic Forest biome in the Northern Espírito Santo, an area of 100 ha. The average rainfall was approximately 750 mm year^{-1} and was spatially and temporally irregular. The average temperature was 26 ºC and the average solar radiation was 26 MJ m^{-2}.

Emergy is defined as the sum of all available direct and indirect energy inputs for a process that is used to provide a product or service. Emergy inputs are expressed in units of energy (usually in solar emergy joules, seJ) (BROWN; ULGIATI, 1997; ODUM; NILSSON, 1996). Solar energy is the primary source that feeds all processes and cycles on Earth. Emergy, or one any the many indicators derived from it, is not an empirical property of an object, but an estimation of embodied energy based on a relevant collection of empirical data from the systems underlying an object, as well as rules and theoretical assumptions, and therefore cannot be directly measured. In the process of emergy evaluation, especially due to its extensive and ambitious scope, the emergy in a object is estimated in the presence of numerical uncertainty, which arises in all steps and from all sources used in the evaluation process (INGWERSEN, 2010). To obtain the emergy of solar energy for a resource or commodity, all resource and energy flows that are used to produce the resource or commodity must be traced. These input flows must be expressed as the amount of solar energy that was used for production (BROWN; ULGIATI, 2002).

Therefore, to perform this analysis, it is necessary to identify the energy sources that act in the sugarcane production system. According to Lanzotti, Ortega and Guerra (2000), the energy sources that influence sugarcane production systems include “rain; wind; sun; agricultural inputs; industrial and urban residues; infrastructure; mechanised operations; physical labour; money and public administration; soil; water; biodiversity and agricultural residues; materials; services; and prices of sugarcane, sugar, and alcohol”.

Observing the attributes and interactions of these systems permits the calculation of emergy generated. Thus, emergy analysis becomes an tool for analysing the environmental and economic impacts of a given production system. Thus, to apply this emergy method for analysing different types of sugarcane harvest, the steps of this method were developed. First, a systemic diagram and an emergy analysis table were prepared. Table 1 presents the form of resource calculation used in emergy analysis.

Next, emergy indices were calculated based on the transformity of each resource, which permitted emergy analysis.

The first step in emergy analysis is to draw a diagram that considers all interactions within a system (a systemic diagram).

Systemic diagrams are used to help us better understand each system component. The system components may be of natural origin (renewable and non-renewable natural resources) or of economic origin (divided between materials, services, and money circulation).

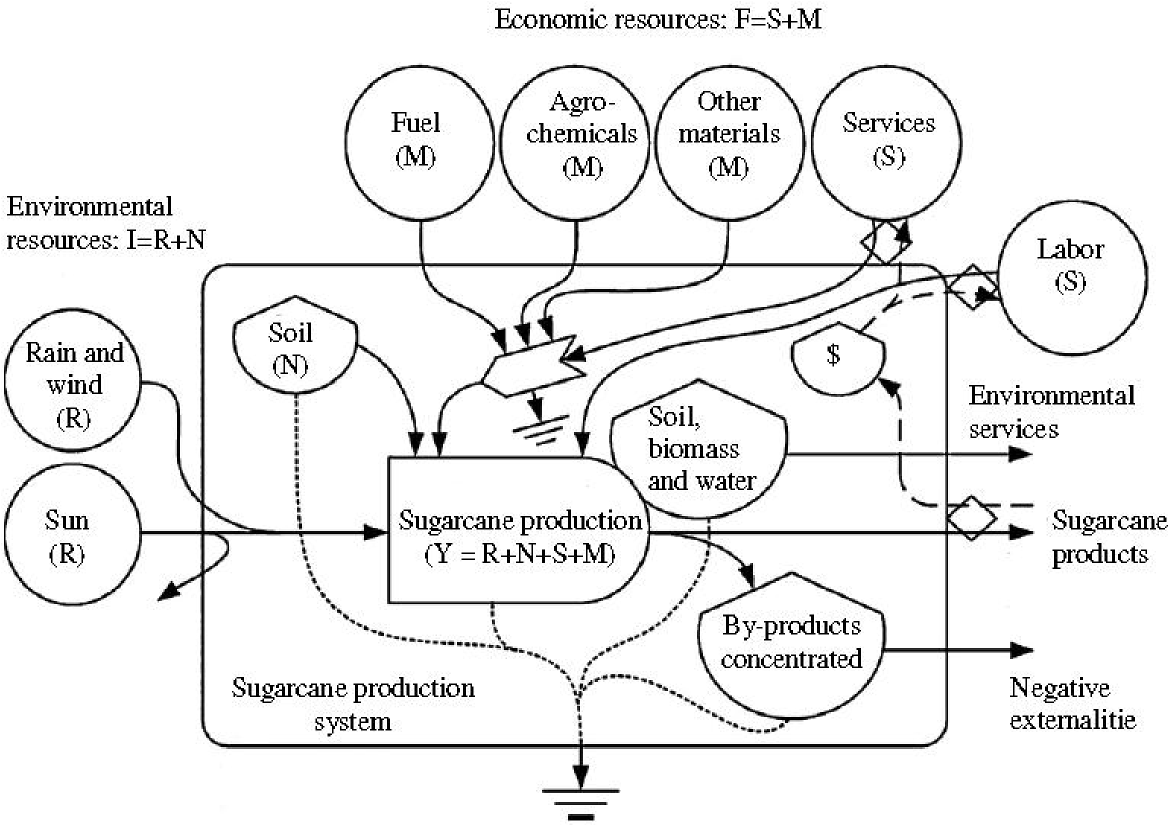
Figure 1 is a general diagram for a production system. The following parameters are included within this diagram: **R = Renewable resources (**direct solar energy, cumulative solar energy, chemical elements from rocks and the atmosphere, local water resources that are freely provided by the system); **N = Non-renewable natural energy** (i.e., represents soil organic matter lost due to erosion); and **F = Economic resources** or the economic feedback of the system. These economic resources are dividing into **M = Monetary resources and S = Services.**

Table 1 - Emergy indices

Index	Formula	Unit
Solar transformity - Tr	Calculated by the sum of all emergy inputs in the process divided by the product energy. The greater the transformity value, the more important the resource for ecosystems and humans	seJ J^{-1}
Renewability percentage - R%	Indicates how much of the energy used in production comes from renewable sources. The greater the value, the greater the system’s sustainability	% seJ/ha/year
Emergy yield ratio	The relationship between the process’ emergy and the sum of all emergies. Indicates if the process returns more to the economy than spent for production	% seJ/ha/year
Emergy investment ratio - EIR	The relationship between all resources that were purchased in the economy (F) and the emergy of the renewable and non-renewable natural resources (N) that are offered by the local environment. This ratio measures the intensity of economic development and environmental load. The greater the ratio value, the greater the economic development. In addition, this ratio can be used to compare various systems to determine which one is more economically competitive	% seJ/ha/year
Environmental load ratio - ELR	The relationship between the sum of the resources purchased (F) and the non-renewable resources (N) divided by the renewable resources (I). The greater this ratio, the greater the environmental impact of the system	% seJ/ha/year
Emergy exchange ratio - EER	The ratio of the product emergy divided by the payment emergy, which is the money received from selling the product. The local economy is compromised when more emergy is sold in the form of products than received in the form of money	% seJ/ha/year

Source: Sousa (2009)

Figure 1 - System diagram



The sum of the renewable (R) and non-renewable (N) resources gives the total contribution (I) to the system. **Thus,** I = R + N the sum of the total nature contributions (I) and the economic contributions (F) provides the total emergy (Y) that is incorporated by the system. Thus, Y = I + F.

After developing the systemic diagrams, we calculated the contributions of all system components. Thus, an emergy analysis table was constructed that includes all inputs that were incorporated into the process and the products, residues, and losses.

After obtaining the values of the indicators shown in the table, the emergy indices are calculated. The main emergy indices include transformity, renewability, emergy yield rate, environmental load rate, emergy investment rate, and emergy exchange rate (KAMIYA; ORTEGA, 2007).

According to Lanzotti, Ortega and Guerra (2000), these indices are used to analyse the environmental impacts and economic conditions of agricultural, forest, and industrial systems. After constructing the emergy diagram and emergy analysis table, we calculate the emergy indices (Table 1).

The first step for applying the emergy method is to construct system diagrams that classify all renewable, non-renewable, environmental, or input components. A system diagram is drawn with the energy language symbols of systems ecology (ODUM; NILSSON, 1996) to represent the system components, sources, emergy flows, and money circulation graphically throughout the system.

The second step in emergy analysis is to tabulate the emergy data by placing the numerical values and units for each flow in the diagram. To obtain the value of each emergy input, the raw input data (such as joules, grams, or dollars) is multiplied by a transformity.

Lastly, the indicators are calculated based on their emergy. In addition, the eco-efficiency, environmental impact, and sustainability of the system studied are evaluated.

RESULTS AND DISCUSSION

Table 2 shows the energy balance in sugarcane production. The total energy flow was 1.76E+16 seJ

Table 2 - Emergy balance of sugarcane production

Resources	Flow (value)	Standard (units)	Emergy flow, mass, and/ or cost	Transformity (seJ unit^{-1})	Emergy flow (seJ (ha year)$^{-1}$)
R					3.30E+15
Rain	1.8	m^3 m^{-2} year^{-1}	9.00E+10	1.83E+04[a]	1.65E+15
Water	3,000	m^3	1.50E+10	1.10E+05[a]	1.65E+15
N					8.01E+14
Soil	12,000	kg ha^{-1} year^{-1}	1.09E+10	7.38E+04[b]	8.01E+14
M					7.65E+15
Seedlings	10,000	kg ha^{-1} year^{-1}	210	3.70E+12[a]	7.77E+14
Limestone	2,500	kg ha^{-1} year^{-1}	2,500	1.00E+12[a]	2.50E+15
Herbicide	2.11	kg ha^{-1} year^{-1}	2.11	8.20E+14[c]	1.73E+15
Fertiliser	500	kg ha^{-1} year^{-1}	500	3.80E+12[c]	1.90E+15
Fuels	358.2	L ha^{-1} year^{-1}	1.12E+10	6.60E+04[a]	7.42E+14
S					5.83E+15
Planting physical labour	0.14	People ha^{-1} year^{-1}	5.35E+08	4.00E+05[d]	2.14E+14
Harvest physical labour	0.12	People ha^{-1} year^{-1}	5.32E+04	1.00E+06[d]	5.32E+10
Administration	351.00	R$ ha^{-1} year^{-1}	3.51E+02	3.70E+12[d]	1.30E+15
Hours/machines	503.5	R$ ha^{-1} year^{-1}	5.03E+02	3.70E+12[d]	1.86E+15
Property rent	225.9	R$ ha^{-1} year^{-1}	2.26E+02	3.70E+12[d]	8.36E+14
Other expenses	438.0	R$ ha^{-1} year^{-1}	4.38E+02	3.70E+12[a]	1.62E+15
Total Emergy				1.78E+11	1.76E+16

a. Odum, Brown and Brandt-Williams (2000); b. Brown and Bardi (2001); c. Brandt-Willians (2002), d. Lanzotti, Ortega and Guerra (2000)

(ha year)$^{-1}$. However, the economic material resources had the greatest absolute value of 7.65E+15 seJ (ha year)$^{-1}$.

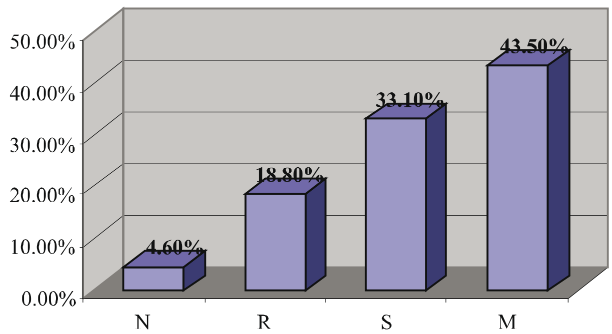
The calculated transformity for sugarcane was 1.78E+11 seJ kg^{-1}. The inputs that were used in sugarcane production represented the greatest proportion of emergy used (43.5% of the total). Services represented the second highest proportion of emergy used (33.1% of the total) (Figure 2).

The greatest aggregate emergy flow value resulted from production factors in the human economy (F), which represented 1.35E+16 seJ (ha year)$^{-1}$ (Table 3).

The sugarcane transformity value, yield ratio, investment ratio, environmental load ratio, renewability ratio, and exchange ratio are presented in Table 4 with values (in equivalent solar energy J^{-1} for sugarcane) values of 4.37, 1.30, 3.29, 4.33, and 18.77, respectively.

Table 5 shows the results of the emergy indices for sugarcane compared relative to other raw materials that are used in ethanol production. Sugarcane has a low transformity relative to other crops. In addition, the

Figure 2 - Proportion of emergy for the four flow categories across all sugarcane production inputs



EYR and ELR values of sugarcane were similar to those of wheat. Overall, sugarcane had the second lowest renewability rate.

Figure 2 shows that inputs are responsible for 43.5% of the total energy flow. This result is explained by the input components, especially for fertiliser (where the main input component is nitrogen). Nitrogen transformity is high relative to other inputs. However, herbicide is another important input that must be discussed. Herbicide uses a large energy flow due to its high transformity value. The transformity of sugarcane could be reduced by partially substituting the nitrogen sources (i.e., with biofertilisers). Regarding herbicide, biological control measures could help reduce herbicide applications and transformity. Sugarcane has a high mechanisation level, which explains 33.1% of the total emergy flow. Non-renewable energy represents 4.6% of the total emergy flow (i.e., sugarcane production is less dependent on this type of input). In contrast, this low dependency is due to the presence of interferences in the soil. For example, interferences that inhibit correcting soil acidity and fertility with inputs.

The sugarcane transformity value is 1.78E+11 seJ kg^{-1}, which is related to the emergy input and sugarcane yield. Transformity can be reduced by using alternative fertiliser sources and biological control agents for pests and weeds. Sugarcane has a lower transformity relative to other raw material crops, which indicates that sugarcane is the best emergy option for appropriate climates. The EYR for sugarcane was only lower than that of wheat, which indicates that sugarcane returns more to the economy than spent on production relative to corn and cassava.

The emergy investment ratio “EIR” is the relationship between economic and natural resources. Because this index is small, the results are reliable. In this case, sugarcane showed better results than corn and cassava.

When more non-renewable resources are consumed, the load on the environment is greater. When humans place excessive loads on the environment, severe degradation regarding ecological systems can occur (BROWN; ULGIATI, 1997). Although sugarcane production uses relatively high levels of technology, the ELR for sugarcane is the second lowest (Table 5). Thus, a lot of room is available for the development of the dominant point-of-view of modern industrialised agriculture.

The environmental load ratio “ELR” is the sum of purchased and non-renewable resources divided by the amount of renewable resources. The greater this index, the greater the environmental impact of the system. In addition, the carbon footprint of a system increases with increasing ELR. Thus, sugarcane production showed better results than wheat and corn.

Table 3 - Aggregated emergy flows for the produced sugarcane

R	3.30E+15
N	8.01E+14
I=R+N	4.10E+15
M	7.65E+15
S	5.83E+15
F=M+S	1.35E+16
Y	1.76E+16

Table 4 - Emergy indices for sugarcane production

Transformity	TR=Y/EP	1.78E+11 seJ kg^{-1}
Yield ratio	EYR=Y/F	1.30
Investment ratio	EIR=F/I	3.29
Environmental load ratio	ELR=(F+N)/R	4.33
Renewability ratio	%R=R/Y	18.77
Exchange ratio	EER=Eprod/Emoney	1.09

Table 5 - Comparison of the emergy indices for ethanol production from four different raw materials

Emergy index	Corn (MARTIN *et al*., 2006)	Wheat (DONG *et al*., 2008)	Cassava (YANG *et al*., 2010)	Sugarcane
TR	1.40E+12	1.82E+12	6.85E+11	1.78E+11
EYR	1.07	1.32	1.11	1.30
EIR	13.8	3.11	9.33	3.29
ELR	18.83	3.47	1.75	4.33
%R	0.06	0.38	0.63	0.19

Therefore, The perspective provided by the sugarcane emergy analysis and synthesis adds new insight to the understanding of the relation of a product with the surrounding environment. It is not just a matter of energy return upon investment, but much more a matter of quality of the resources invested (and therefore a matter of suitability of the investment). One joule of electricity is not the same thing as 1 J of solar radiation or 1 J of wood or organic matter in the soil. The quality of input flows, their being local or imported, their being renewable or nonrenewable, their larger or smaller demand for environmental support, make a product more or less valuable according to what driving forces were invested by nature to make it and for how much time. Something that requires a large environmental work will also be hardly replaced through the same environmental dynamics and therefore may not be the best resource base for an economic system to be sustainable. The same set of emergy input flows, each characterized by a given transformity and quality, could be used to drive an alternative system or development strategy with much better results. Other studies have shown this trend, (DONG *et al.*, 2008; HOFSETZ; SILVA, 2012; SOUZA, *et al.*, 2014).

CONCLUSIONS

1. Emergy analysis is an adequate method for identifying and assessing production system inputs of renewable and non-renewable energy in the sugarcane production industry. In addition, emergy analysis allows several energy flows to enter the evaluation process, including environmental, monetary, and labour resource flows;
2. Overall, 43.5% of the entire emergy system resulted from inputs, especially those of fertilisers and herbicides. The nitrogen dependency of chemical fertilisers reduces the fraction of renewable energy and increases environmental degradation. Thus, nitrogen dependency results in less sustainable sugarcane production. The use of alternative fertiliser sources can enhance sustainability and reduce the system's environmental load;
3. Sugarcane production as raw material for ethanol production in Brazil is more emergetically sustainable than corn, wheat, and cassava production.

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