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COMPARATIVE EMERGY EVALUATION OF CASTORBEAN (*RICINUS COMMUNIS*) PRODUCTION SYSTEMS IN BRAZIL AND THE U.S.

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ABSTRACT

Castorbean (*Ricinus communis* L.) oil is critical to many industrial applications because of its unique ability to withstand high and low temperatures. On a per mass basis, it has a higher price than the ubiquitous lubricants and fuel additives made from crude oil. Brazil's fuel alternatives programs have experimented with Castorbean production mainly in the arid northeast but more recently in the southwestern state of Mato Grosso do Sul. In this paper we determine whether Brazilian Castorbean production provides a net benefit (i.e., net emergy yield) and whether Brazilian methods are more sustainable than U.S. methods used during the 1960's, when the U.S. was a large producer and exporter of Castorbean oil. We applied the environmental energy accounting method of emergy evaluation to assess Castorbean production in the south-central United States (Texas) and in southwestern Brazil (Mato Grosso do Sul). Emergy evaluation assesses environmental and economic sustainability based on the total amount of natural and human resources used to make a product. Emergy answers the question of how much it costs nature to produce a specific product or support a given process by converting all resource flows (e.g., environmental, human-controlled, fuels) to the total amount of solar energy required for their existence. This is called solar emergy (Odum, 1996), which has units of solar emergy joules (sej). Castorbean production required a slightly greater amount of solar emergy per joule in the U.S. in 1960 than in Brazil in 2004, with a solar transformity of 100,604 seJ J^{-1} for the former and 89,811 seJ J^{-1} for the latter. The Emergy Yield Ratio (EYR) was 1.70 for Brazil and 2.27 for the U.S., which were both greater than the break-even point of 1.0, indicating that Castorbean had some potential as a biofuel, but was far less competitive than most fossil fuels. The Environment Loading Ratio was 2.19 for Brazil and 7.25 for U.S., indicating that the Brazilian system had less environmental impact and relied more on renewable energy sources. The emergy evaluation identified Brazilian Castorbean production as a potentially sustainable, yet weak, source of biofuel for the future that can provide more value to the economy than it diverts, but presently would compete poorly with fossil fuels that have higher EYR (6.0+).

1. INTRODUCTION

Since the oil crisis of the mid 1970's, besides developing its offshore drilling capacities to achieve greater oil independence, Brazil developed its offshore drilling capacities to achieve greater oil independence and invested in a number of fuel alternatives, from timber gasification processes to methanol extraction from sugar cane, generating a number of biofuel programs around the country, but principally in the arid Northeast. Some of the alternatives promoted the use of Castorbean oil, a practice that is now used in the southwestern state of Mato Grosso do Sul.

The study is motivated by the high potential alternative fuel value of Castorbean oil, which also has many other uses. In the medical field, blood filters, can be made from Castorbean oil, and internal and external body pumps and bone prostheses can be made of Castorbean resin, a lighter material than platinum with no observed rejection problem (Azevedo et al., 1961). The oil is also used in the car and construction industries, in coatings, special paints, varnishes, detergents, candles, synthetic products, adhesives, isolating resins, special glues, grease for ships, cosmetics, contact lenses and to assist fluid dynamics in hydraulics.

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Mato Grosso's 2003 Castorbean bean production was estimated at 8,750 MT for 3500 ha planted. North Eastern Brazil set up an Integrated Development Project with a focus on Bio-Diesel production, where oil from Castorbean would be the main component. This would offer small producers an opportunity to invest in a crop with a guaranteed sales price, but called for a state-of-the-art organization of producers that could guarantee quantity and quality.

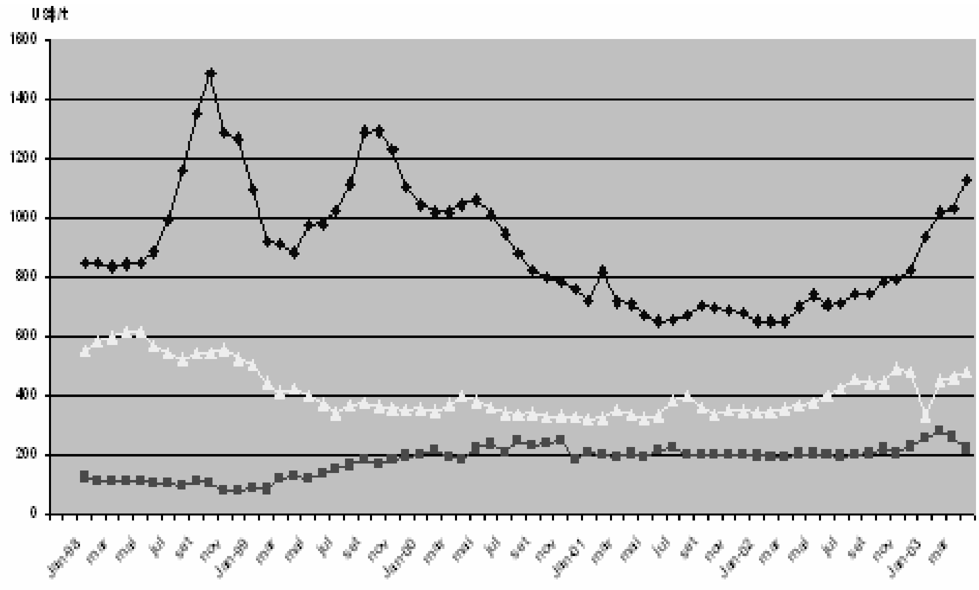

Figure 1. Comparative prices of Castor oil (top curve), crude soy oil (middle curve), and crude oil (lower curve) (http://www.conab.gov.br/download/cas/semanais/Semana08a12092003/Conj-Mamona-08a1209031.pdf), (Martha, H.G. Macedo, 2003).

However, there is a need to understand how effective for the overall Brazilian economy are these alternative energy sources and processes in substituting crude oil use. In this paper, we investigate whether Brazilian Castorbean production provided a net benefit (i.e., net emergy yield) and attempt to quantify whether Brazilian methods are more sustainable than U.S. methods used during the 1960's when the U.S. was a large producer and exporter of Castorbean oil.

In order to compare the two systems, we employ the environmental accounting theory of emergy evaluation. Emergy approaches the question of environmental and economic sustainability starting from the production end; that is, how much does it cost for nature to produce a specific product or process. Emergy theory calculates the amounts of resource flow to the system under study in solar energy equivalent units (solar emergy Joules - sej/unit time). Although weather, soil and social conditions are vastly different in the two systems compared, the emergy evaluation can shed important light on the relationship between incoming natural resources and human contributions to the production process.

2. OBJECTIVES

The main objective of this paper is to determine whether Castorbean production in the south-western Brazilian State of Mato Grosso do Sul provides a net public benefit (i.e.,

net emergy yield) and to quantify whether current Brazilian methods are more sustainable than U.S. methods during the 1960's.
The approach is to evaluate the Castorbean oil production in both systems on a per hectare basis, quantifying incoming and outgoing energy flows, energy stocks and paths within the system, and then calculate in emergy terms the net benefit, or net emergy yield, and other useful emergy indices.

2.1. International trends

The 60% rise in international prices of Castor oil, after the announcement of the war on Iraq, caused increased oil production in Brazil. In April 2003, a ton of Castorbean oil was sold at US$ 1,100, more than double the price of soy oil, quoted for US$ 500/ton, and five times more than the West Texas Intermediate ton of crude, sold for US$ 215/ton in New York (Figure 2).

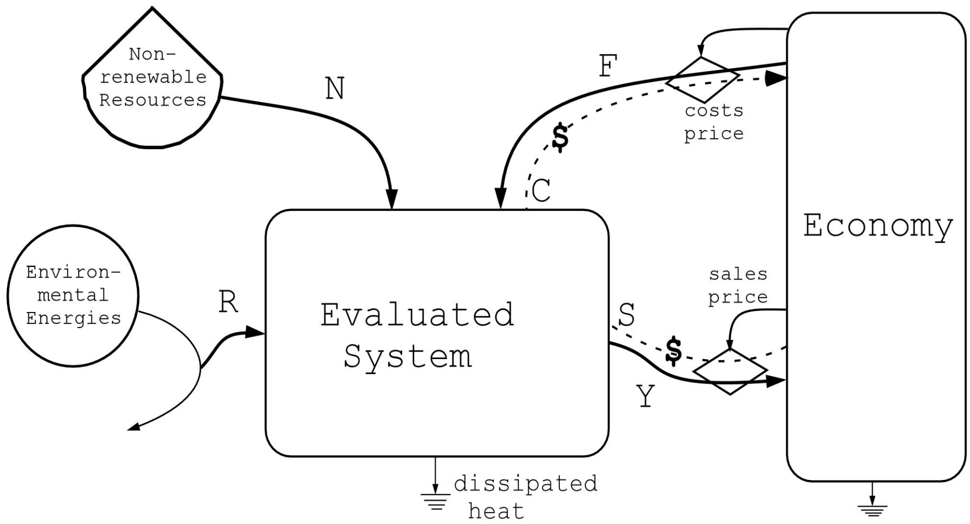

Figure 2. Energy systems diagram of the aggregated inputs (R, N, and F) to an evaluated system that produces a yield (Y) to the economy and generate sales revenue (S) which is pays for purchased costs (C)

Mato Grosso's Castorbean oil production in 2003 was estimated at 8,750 tons for 3500ha planted. In 2004 North Eastern Brazil has set up an Integrated Development Project with a focus on Bio Diesel production, where oil from Castorbean would be the main component. This project called for an increase in the quantity and quality of castorbean oil production, and many small producers were considering substituting corn and other secondary crops for the short-cycle Castorbean, since the latter would have a guaranteed sale.

3. MATERIALS AND METHODS

3.1. Castorbean characteristics

Of Afro-Asiatic origin, Castorbean has been found in Ethiopia, in the region of Sennarr, Kordofan and in India. Its seed were even found in the great Egyptian pyramids, by the side of the pharaohs (Savy et al. 1999a). In Brazil, Castorbean grows as a bushy plant, varying in height in its mature stage between 1.80 to 3.50 m, with a pivoting root, which can reach up to 1.5 m in depth and lateral horizontal roots up to 80 cm. The aerial part of the plant branches out with a green or reddish color, according to its variety. It is plant with masculine and feminine flowers such that its inflorescence contains feminine flowers in the superior part and masculine ones in the inferior one. It can produce from 1,500 to 5,000 kg/ha of seeds.

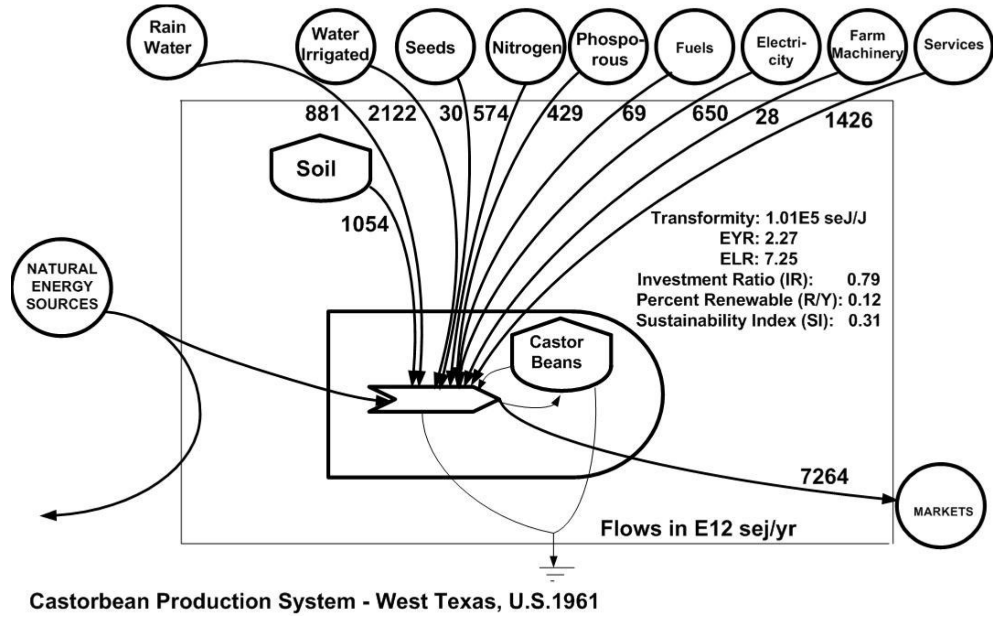

Figure 3. Systems diagram of Castorbean production in U.S. (West Texas) in 1961

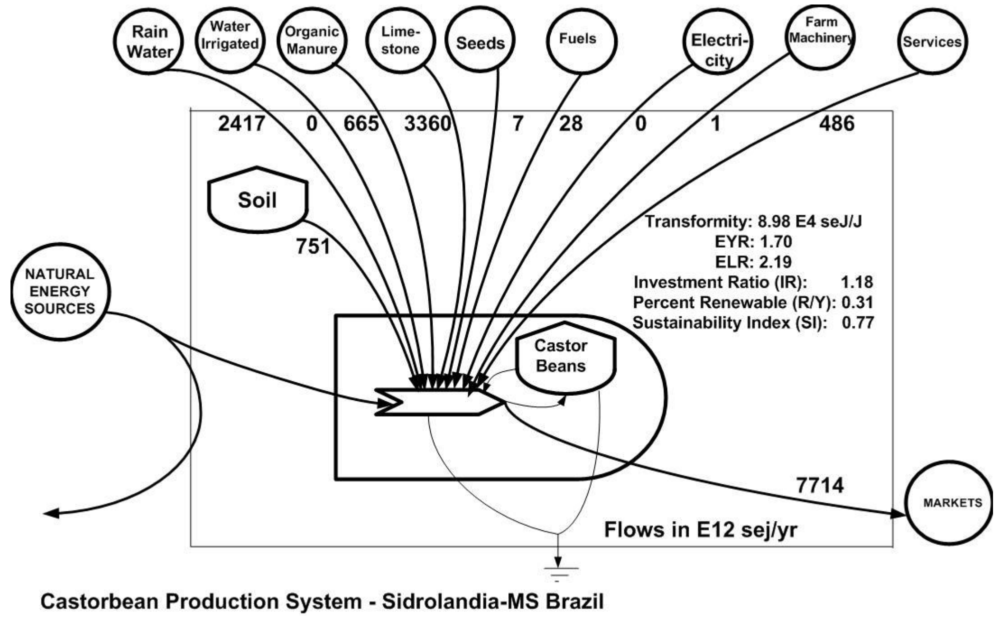

Figure 4. Systems diagram of Castorbean production (Mato Grosso do Sul in 2003)

As a tropical and sub-tropical plant, it finds excellent growing conditions in Brazil, as it needs regular rainfall at the beginning of its growth cycle, and dry periods for the maturing of its fruits (Savy et al., 1999b). In relation to soil conditions, it grows well where corn crops are successful, in fields with good sun exposure with less than 12% slope. Castorbean prefers deep and well drained, loamy-clay and clay soils. Alluvial soils are excellent for the Castorbean plant, which doesn't reach a good production in humid or poor soils. Because of high soil loss, this plant should be associated with other crops, such as beans, corn and other vegetables, to protect the soil from erosion and provide additional revenues. It is recommended for small producers using family manpower for its cultivation (Savy et al., 1999b).

3.2. Castorbean cultivars

Although many varieties exist, research in the Brazilian State of Sao Paulo, by the Institute of Agronomy of Campinas (IAC), recommends three types: the IAC-80, IAC-226 and the IAC-Guarani (http://www.iac.sp.gov.br/Cultivares/, consulted 15th October 2004, 10:15h). The latter was used in our study for the Brazilian system. The IAC 80 variety has a tall stem, reaching up to 2.5 to 3.0m at the end of its vegetative cycle. All varieties produce seeds which vary between 47 to 48% of oil content. (Savy et al. 1999a).

3.3. Environmental Accounting with Emergy

Agricultural systems in general depend on inputs from both nature (precipitation, soil, etc.) and the human economy (labor, fuels, etc.). Typically, high quality, non-renewable energies from the human economy are coupled to lower quality, more abundant renewable energies of nature. Intensive agricultural methods rely more on resources purchased from the economy, while less intensive and indigenous methods typically rely more on natural inputs. Because most types of agriculture depend on a combination of natural and economic inputs, it is necessary to account for both in equivalent terms when comparing resource intensity of different agricultural systems (Campbell 1998). Performing such an environmental accounting, can provide quantitative measures of system sustainability.

Emergy evaluation is an environmental accounting method that addresses the issue of environmental and economic sustainability by quantifying the total amount of natural resources that nature spends (i.e., dissipates) and the total amount of economic resources are consumed to produce a product or operate a service. The emergy evaluation method involves calculating the ultimate amount of solar energy responsible for providing all of the energy, material and financial inputs that were required to drive a system. Thus, all system resource inputs are translated to their solar energy basis, which are called solar emergy joules and abbreviated seJ. A history and review of applications of the emergy method was recently given by Brown and Ulgiati (2004). Due to emergy's ability to compare environmental and economic resources used in agricultural production, emergy analysis can assess a system's sustainability based on indices that relate the free work of nature based on renewable inputs to non-renewable resource consumption, agricultural yield and economic investment. A fundamental assumption of emergy analysis is that the worth of a contributed resource to agricultural production is proportional to its solar emergy, i.e., the total amount of solar energy dissipated directly and indirectly (Brown and Herendeen 1996). Although weather, soil and social conditions are vastly different between Brazil and the U.S., the emergy evaluation can shed important light on the relationship between natural resource contributions and human contributions by comparing total emergy requirements, emergy indices, and solar emergy used per unit of energy produced (i.e., solar transformity).

The general methods for employing emergy synthesis have been extensively covered by Odum (1996, 2000a). For our analyses, the solar emergy of an input to Castorbean production was either the product of its available energy (J) and solar transformity (seJ/J), the product of its mass (g) and its specific solar emergy (seJ/g), or the product of its nominal dollar amount ($) and the emergy-to-dollar ratio (seJ/$) of the country for the specific year. Solar transformities and specific solar emergies were taken from past emergy publications with specific instances given in table footnotes. The solar emergy-to-dollar ratio for the U.S. in 1960 was taken from Tilley (2004), and Brazil's was from Coelho, Ortega and Comar (1998).

Representing the free environmental emergy and the human-controlled emergy in similar units allows for the easy comparison between the environmental and economic contributions to Castorbean production. A relative measure of environmental sustainability is quantified using the emergy index known as the Environmental Loading Ratio, ELR (Brown and Ulgiati, 1999), which is the total human-controlled emergy invested in the crop production divided by the total amount of free environmental emergy. An emergy-based metric used to judge whether a fuel provides a net amount of solar emergy to an economy is called the Emergy Yield Ratio, EYR (Odum, 1996), which is defined as the total emergy assigned to the output per unit of emergy invested from the economy. Fossil fuels have been found to have EYR's ranging from 4:1 to 40:1 (Odum 1996). The higher the EYR, the greater is the return on emergy invested to extract and process the fuel. By definition, the minimum EYR is 1.0.

Definitions of terms and indices (refer to Figure 1 for symbol definitions):

Emergy: the available energy (exergy) of one kind that is used in the transformations directly and indirectly to make a product or service. Emergy is measured in emergy-joules (emjoules). Sunlight, fuel, electricity, and human service and all other resource flows can be put on a common basis by expressing them in the emjoules of solar energy required to produce them, which is called expressed as solar emjoules (seJ).

Transformity: the ratio of emergy input to available energy (exergy) output. For example, the solar transformity of wood is 4000 solar emjoules per joule (seJ/J) because 4000 solar emjoules of environmental inputs were required to generate a joule of wood. The solar transformity of sunlight absorbed by the earth is set to 1 seJ/J by definition.

Specific emergy: the emergy per unit mass output. This is usually expressed as solar emergy per gram (seJ/g).

Emergy per unit money: the emergy supporting the generation of one unit of economic product (expressed as currency). The average emergy/money ratio (seJ/$) can be calculated by dividing the total emergy use of an economy by its gross economic product (e.g., GDP).

Empower: the flow of emergy per unit of time. Emergy flows are usually expressed in units of solar empower (i.e. seJ/yr).

Emergy Yield Ratio (EYR=Y/F): emergy cost of the yield (Y) produced (Y=R+N+F) per unit of emergy contributed by the main economy (F) (seJ/seJ)

Environmental Loading Ratio (ELR=(N+F)/R): emergy contributed by non-renewable and economic sources per unit of emergy contributed by renewable resources (seJ/seJ) It is an indicator of the pressure of agricultural systems on the environment and may be considered a signal of possible ecosystem stress (Ulgiati and Brown, 1998).

Emergy Sustainability Index (ESI=EYR/ELR): is the ratio of yield to environmental load, which measures system production relative to environmental pressure (Ulgiati and Brown, 1997).

Emergy Investment Ratio (EIR=F/(N+R)): emergy purchased and contributed from the economy (F) per unit of emergy contributed free from the environment whether renewable or non-renewable (R+N)

4. RESULTS AND DISCUSSION

Tables 1 and 2 present the assessment of solar emergy inputs to Castorbean production and give emergy-based indices. Irrigation water was the largest input for the U.S. system, while limestone was the largest in Brazil. Brazilian energy and emergy yield were both 19% greater than in the U.S. This resulted in the solar transformity of castorbean oil to be 100,604 seJ J^{-1} for the U.S. system and 89,811 seJ J^{-1} for the Brazilian one.

Table 1. Solar emergy values of inputs to Castorbean production (1 ha) in south-central U.S. (West Texas) in 1961

	Input	**value**	**unit**	**Solar Emergy per unit (seJ $unit^{-1}$)**	**Solar Emergy ($1x10^{12}$ seJ ha^{-1} y^{-1})**
"Free" Renewable Inputs (R)					
1	Sun	3.77E+13	J	1	38
2	Wind	2.90E+11	J	2513[1]	729
3	Water, Rain	2.88E+10	J	30576[1]	881
"Free" Non-renewable (N)					
4	Soil loss	1.43E+10	J	73800[1]	1054
5	Water, Irrigation	8.65E+09	J	245280[1]	2122
Purchased (F)					
6	Nitrogen	9.00E+04	g	6.38E+09[1]	575
7	Phosphorus	4.50E+04	g	9.53E+09[1]	429
8	Fuels	1.04E+09	J	66000[1]	69
9	Seed (energy, J)	5.21E+08	J	5.85E+04[2]	30
10	Electricity	2.84E+09	J	2.29E+05[1]	650
11	Farm Machinery	2203	g	1.25E10	28
12	Human services	129.63	$	1.10E+13[1]	1426
Yield (Y)					
	Emergy	7.42E+13	seJ		7264
	Mass	1.92E+06	g		
	Energy	7.22E+10	J		

[1] Transformity (Odum, 1996) corrected by factor of 1.68 (Odum et al., 2000)
[2] Transformity (Odum and Odum, 1983).

Table 2. Solar emergy value of inputs to Castorbean production (1 ha) based on a small-scale family agricultural plantation (Capao Bonito in Sidrolandia) located in Mato Grosso do Sul, Brazil

Notes	Input	value	unit	Solar Emergy per unit (seJ unit $^{-1}$)	Solar Emergy ($1x10^{12}$ seJ ha^{-1} y^{-1})
"Free" Renewable Inputs (R)					
1	Sun	3.85E+13	J	1	39
2	Wind	5.10E+10	J	2513[1]	128
3	Water, rain	7.90E+10	J	30576[1]	2417
"Free" Non-renewable (N)					
4	Soil loss	1.02E+10	J	73800[1]	751
5	Water, irrigation	0	J	-------	0
Purchased (F)					
6	Organic Manure	2.51E+10	J	2.65E+04	665
7	Limestone	2.00E+06	g	1,68E+09	3360
8	Fuels	4.18E+08	J	66000	28
9	Seeds (energy, J)	1.25E+08	J	5.85E+04[2]	28
10	Electricity		J		
11	Farm Machinery	9,13E+01	g	1,25E+10	1
12	Human services	60	$	8.10E12[1]	486
Yield (Y)					
	Emergy	7.71E+15	seJ		7714
	Mass	2.28E+06	g		
	Energy	8.59E+10	J		

Table 3 compares total emergy inputs for each country's production system. The U.S. system irrigated with groundwater, which was a 'free' non-renewable input not used in Brazil. Soil loss was a common contribution that was 40% higher in the U.S. Precipitation (881E12 seJ ha^{-1}y^{-1} for U.S. and 2,416 E12 seJ ha^{-1}y^{-1} for Brazil) was the largest 'free' renewable input in both systems.

In the Brazilian system, the organic manure used as fertilizer (665 E12 seJ ha^{-1}y^{-1}) contributed less solar emergy than the chemical-based nitrogen and phosphorous fertilizers used in the U.S. (1004 E12 seJ ha^{-1}y^{-1}). The dollar costs of U.S. labor were more than twice Brazil's ($129 against $60), but nearly three-fold more in solar emergy due to the higher emergy-to-money ratio of the U.S. in 1960.

The Emergy Yield Ratio (EYR) was greater for the U.S. system. The U.S. system used more free environmental inputs and less purchased economic inputs. However, a large portion of U.S. environmental input was from non-renewable soil and groundwater. The U.S. had an environmental load (ELR) of 7.25, whereas Brazil's was significantly smaller at 2.19, which showed that the U.S. system used more economic and non-renewable resources per unit of indigenous, renewable resource. The Emergy Sustainability Index (ESI was 0.31 for U.S. and 0.77 for Brazil, while a related index, the percentage of total emergy yield generated from renewable inputs, was 12.12% for

[1] Transformity (Odum, 1996) corrected by factor of 1.68 (Odum et al., 2000)
[2] Transformity (Odum and Odum, 1983).

U.S. and 31.33% for Brazil. Both of these metrics were sensitive to the greater use of non-renewable inputs in the U.S. According to these two indices, the Brazilian system was more than twice as 'sustainable,' but both systems had low values according to Brown and Ulgiati (1997), which suggest that the net emergy was provided at the expense of a high environmental load.

Table 3. Comparison of emery evaluation of Castorbean production in U.S. and Brazil

	Input	US (Texas) Solar Emergy ($1x10^{12}$ seJ ha^{-1} y^{-1} unless noted otherwise)	Brazil (Mato Grosso do Sul) Solar Emergy ($1x10^{12}$ seJ ha^{-1} y^{-1} unless noted otherwise)
"Free" Renewable Inputs			
	Sun	38	39
	Wind	729	128
	Water, rain	881	2417
"Free" Non-renewable			
	Soil loss	1054	751
	Water, irrigation	2122	0
Purchased			
	Nitrogen	575	0
	Phosphorus	429	0
	Organic manure	0	665
	Limestone	0	3360
	Fuels	69	28
	Seeds (energy, J)	30	7
	Electricity	650	0
	Farm Machinery	28	1
	Human services	1426	486
Yield			
	Emergy (seJ ha^{-1} y^{-1})	7264	7714
	Mass (g ha^{-1} y^{-1})	1,920,000	2.28E+06
	Energy (J ha^{-1} y^{-1})	7.22E+10	8.59E+10

Indices

Solar Transformity (seJ J^{-1})	**1.01E5**	**8.98E+04**
Yield to Purchased (EYR=Y/F)	**2.27**	**1.70**
Environmental Loading Ratio (F+N)/R	**7.25**	**2.19**
Emergy Investment Ratio F/(N+R)	**0.79**	**1.18**
Percent renewable (R/Y)	**12.12%**	**31.33%**
Emergy Sustainability Index (ESI) (EYR/ELR)	**0.31**	**0.77**

The Emergy Investment Ratio (EIR) was greater for the Brazilian system (1.18) compared to the U.S. (0.79), indicating that the Brazilians had to divert more investment from their economy per unit of contribution from the environment than did the U.S. The smaller EIR for the U.S. reflects the greater contribution made by the two free, non-renewable resources, soil and groundwater. In other words, economic investment in U.S. castorbean production enjoyed a greater subsidy from the environment than in Brazil, albeit a subsidy that could not be sustained.

It is remarkable that, in light of different crop treatments and the disparity in the time periods during which the systems operated, the resulting difference in solar transformities is just of 10.73% (1.01 E5 seJ J^{-1} for the U.S. system and 8.98 E4 seJ J^{-1} for Brazil's).This discovery supports the notion that optimized agricultural systems can only substitute inputs on an equal emergy basis (e.g., mechanization for unskilled labor, or manure for chemical fertilizers). A 10-fold increase in seed price from US$0.05 lb^{-1} to US$0.50 lb^{-1} would only increase the solar transformity by 1.4% to 132,900 seJ J^{-1}, and increase environmental loading (ELR) and investment (EIR) slightly to 10.0 and 1.39, respectively.

A substantial difference in crop production methods that increased the solar transformity of Brazilian Castorbean was due to the need to add limestone to correct soil acidity. The addition of limestone resulted in more than three times the emergy added from nitrogen and phosphorous in the U.S. Since we did not know the true solar transformity of Brazilian limestone, we used the value given by H.T. Odum (1996). A future analysis could refine the Brazilian solar transformity of Castorbean by estimating a Brazilian solar transformity for limestone.

The U.S. production system's environmental load (ELR) was 3.31 times greater, which was due to irrigation with non-renewable ground water [i.e., more N in the ELR equation, (F + N)/R] and partly because West Texas precipitation was only one-third of Brazil's (i.e., lower R in (F + N)/R). Higher soil erosion in the U.S. was also a factor in creating a higher ELR for the U.S.

The yield ratio (EYR) was greater for the U.S. indicating that the U.S. was more efficient in the sense of getting more output per unit of input. The country differences were mainly due to the limestone input in Brazil. The Brazilian EYR could be increased if less limestone was used. It may also be that replacing organic manure with nitrogen and phosphorous fertilizers would bring down the emergy inputs, which would raise the EYR.

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