

# Accounting energy flows to determine the best production model of a coffee plantation

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## ARTICLE INFO

### Article history:

Received 2 March 2011

Accepted 2 September 2011

Available online 22 September 2011

### Keywords:

Coffee production

Emergy

Energy flows

## ABSTRACT

Cerrado, a savannah region, is Brazil's second largest ecosystem after the Amazon rainforest and is also threatened with imminent destruction. In the present study emergy synthesis was applied to assess the environmental performance of a coffee farm located in Coromandel, Minas Gerais, in the Brazilian Cerrado. The effects of land use on sustainability were evaluated by comparing the emergy indices along ten years in order to assess the energy flows driving the production process, and to determine the best production model combining productivity and environmental performance. The emergy indices are presented as a function of the annual crop. Results show that Santo Inácio farm should produce approximately 20 bags of green coffee per hectare to accomplish its best performance regarding both the production efficiency and the environment. The evaluation of coffee trade complements those obtained by contrasting productivity and environmental performance, and despite of the market prices variation, the optimum interval for Santo Inácio's farm is between 10 and 25 coffee bags/ha.

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## 1. Introduction

Historically, coffee production in Brazil has been marked by several cycles of territorial occupation and environmental imbalance caused by disordered replacement of natural ecosystems and soil degradation by broad farming areas. The share of coffee in total exports in monetary values declined from 70% at the end of the 1920s to around 40% in the 1960s, to less than 10% in the 1980s and around 5% in the 1990s (Paiva, 2000). Coffee had many secondary effects on Brazilian economy history such as the campaign for the slavery abolition, employment of free immigrant labor, foreign investment in infrastructure, capital accumulation of coffee growers, and the derived growth of coffee industry (Baer, 2001).

Beyond the obvious social component, sustainable development should consider economic, environmental, and political aspects. The environmental component of sustainable development focuses on respecting the support capacity of ecosystems, while the economic component addresses the rational and efficient use of energy flows that feed the system. In this way, only a systemic view may maintain development along time without degradation of any of its constituting elements. In this context, trackability emerged as an important tool developed to ensure a safe, high quality product dependent on a responsible management. Though only a small share of the global coffee trade is

currently certified, voluntary certification and labeling initiatives are becoming increasingly important vehicles for regulating sustainability in coffee, as well as for other commodities (Raynolds et al., 2007). Coffee from Cerrado was the first to receive this type of certification and its bar code includes information about its origin and production characteristics (Crestana et al., 2009). Nevertheless, there are important differences between certifications that delimit potential impacts, and there are also restrictions to the degree to which these initiatives contribute to sustainable development.

Adams and Ghaly (2007a) examined the current coffee production and processing system in Costa Rica in order to maximize its sustainability through cost and risk reductions and identification of new opportunities. A two-year field investigation was performed for assessing resource, energy and water use, characterizing by-products, and evaluating training, management and industry structure, with the aim of identifying opportunities for the implementation of cleaner production and industrial ecology strategies. However, the application of these strategies has not been accepted by the Costa Rican industry. According to the authors, the coffee production system in Costa Rica does not encourage the practice of environmentally sustainable methods within production or processing. Recording the stakeholders' perceptions in order to ensure a proper match between sustainability barriers and the steps to address it, Adams and Ghaly (2007b) recognized a significant gap between the requirements of a sustainable industry and the actual system. The inclusion of stakeholders' thoughts and perceptions was identified as an

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important factor in the establishment of policies aiming to improve the overall sustainability of the coffee industry.

The environmental impact of coffee production has been analyzed with the use of life cycle assessment (LCA). Salomone (2003) assessed the environmental management practices in an Italian coffee company, and related the main categories of environmental impact to the coffee cultivation stage. A comparison between impacts associated with alternative packaging systems on the supply of coffee (De Monte et al., 2005) suggested that the use of poly laminate bags for small size packages could be an alternative, even though this solution does not favor material recycling. Humbert et al. (2009) evaluated the environmental burdens associated with spray dried soluble coffee over its entire life cycle and compared it with drip filter coffee and capsule espresso coffee. This assessment showed that about one half of the environmental impact occurs at a life cycle stage under the control of the coffee producer and the other half at a stage controlled by the user (shopping, appliances manufacturing, use and waste disposal). In Brazil, the first life cycle inventory was conducted among the 56 participants to the establishment of an environmental profile for coffee cultivation (Coltro et al., 2006). The large variation of the amount of agricultural inputs evidenced a clear opportunity for the reduction of some of these inputs (Coltro et al., 2006).

The central role of energy in all life processes has led to the development of numerous hypotheses, conjectures and theories on the relationships between thermodynamics and ecological processes. Emergy accounting is widely practiced in evaluating the energy flows driving agricultural systems (Lagerberg and Brown, 1999; Qin et al., 2000; Guarnetti et al., 2006; Almeida et al., 2007; de Barros et al., 2009; Agostinho et al., 2008; Cavalett and Ortega, 2009; Bonilla et al., 2010; Pereira and Ortega, 2010; Giannetti et al., 2011). Regarding the use of resources, Sarcinelli and Ortega (2004) pointed out that better economic results could be achieved when small coffee producers made larger use of their renewable natural resources. Comparing a traditional production system with the production of organic coffee, these authors concluded that the organic system may improve the economic results of small properties using more permanent employees per area. Cuadra and Rydberg (2006) published an emergy evaluation of coffee production, processing and export in Nicaragua. The environmental contribution to tradable products and its role in a fair trade were evaluated with the use of emergy indices. Nicaragua depletes its local natural resources exporting much more emergy in the green coffee sold than it imports in the money received for it (Cuadra and Rydberg, 2006). The emergy exchange ratio indicates that almost all purchasers benefit when buying green coffee from Nicaragua, while the sales of roasted or instant coffee are of benefit for Nicaragua.

This study using emergy synthesis focuses on Cerrado, which produces most of the quality coffee exported from Brazil. The Brazilian coffee farm is located in the Southern part of the state of Minas Gerais, and was evaluated to:

- assess the energy flows driving the production process,
- assess the emergy indices as function of the green coffee productivity,
- determine the best production model combining productivity and environmental performance,
- determine the best production model combining sales and environmental performance.

## 2. Methods

Emergy is defined as the available energy previously required, directly and indirectly, through input pathways to make a product

or service. The unit of emergy is solar emergy joules (sej). The emergy flows represent three categories of resources: *R* as renewable resources, *N* as non-renewable resources and the inputs from the economy, *F*. *R* and *N* flows are provided by the environment and are economically free. The economic inputs, *F*, are provided by the market and related to fluxes that are accounted by the economy. Services provided by humans with a higher level of education were separated from manual labor. Farm management and consulting services were accounted according to the money paid for each service (Brandt-Williams, 2002). The emergy embodied in financial resources from human-derived services was also inferred from the price of imported items (Cuadra and Rydberg, 2006; Dong et al., 2008).

The quotient of a product's emergy divided by its energy is defined as its transformity (Odum, 1996). Transformity, given in sej/J, puts together emergy and energy, and refers to the emergy needed to obtain 1 J of a product or service, directly or indirectly. The more energy transformations there are contributing to a product, the higher is its transformity. This is because at each transformation, available energy is used up to produce a smaller amount of energy of another form. When transformations are arranged with different inputs, different combinations of speed and efficiency result. The transformity that accompanies the optimum efficiency for maximum power transfer has a theoretical lower limit that systems may approach after a long period of self-organization. The most efficient transformations are those that have been in environmental and economic competition for a long time (Odum, 1996).

Values of the transformities used in this text are mostly taken from the literature, and are relative to the  $15.83 \times 10^{24}$  sej/year baseline (Odum and Odum, 2000). Although the appropriate value for the baseline is still in discussion (Campbell, 2000; Campbell et al., 2004, 2005; Brown and Ulgiati, 2010) the use of a given baseline allows comparing results with transparent calculation procedures. Transformities calculated using the  $9.44 \times 10^{24}$  sej/year baseline have been multiplied by 1.68 to obtain the updated values.

Emergy indices were employed to assist the discussion: the environmental loading ratio (ELR), the emergy yield ratio (EYR), the emergy investment ratio (EIR) and the emergy index of sustainability (ESI). A brief description of the emergy indices is shown in Table 1.

EER is the ratio of emergy exchange in a trade or purchase (Odum, 1996). It assesses the advantages or disadvantages in terms of price paid for coffee, and was calculated converting currency flows to emergy units. When a good is sold and money is received in exchange, this ratio gives a measure of the relative trade advantage of one partner over the other.

Different countries have different emergy/\$ ratios, as already shown by Odum (1996), Rydberg and Jansen (2002) and Brown and Buranakarn (2003). Balanced trade is accomplished when emergy of imports and exports of trading partners is equal (Brown and Buranakarn, 2003). However, emergy evaluations often show that such exchanges are not equal (Odum, 1996). Germany, which is a major buyer of the Brazilian coffee has as EMR of about  $2.81 \times 10^{12}$  sej/US\$, while that of Brazil is  $1.12 \times 10^{13}$  sej/\$ (NEAD, 2009). Then, Brazil has a trade disadvantage of approximately 4 times trading with Germany. A weighted average EMR ( $3.05 \times 10^{12}$  sej/\$, Table 2) for importing countries representing about 60% of total exports of Cerrado's coffee (MDIC, 2008) was calculated for the years 1999–2004 on the basis of their contribution to the Brazilian gross domestic product (GDP). The EMR of the six countries was considered constant for the period of 1999–2004, and the values were taken from NEAD (2009).

Emergy evaluation tables, prepared according to the procedures described by Odum (1996), were used to assess the coffee production process from 1997 to 2006 and the farm sustainability.

**Table 1**  
Energy based indices, description and references on the possible range of values for each index.

Indices	Description	Range
$EYR = \frac{U_{coffee}}{F}$	The emergy yield ratio (EYR) is the ratio of the emergy of the output ( $U_{coffee} = R + N + F$ ), divided by the emergy of those inputs ( $F$ ) to the process that are fed back from outside the system.	$EYR < 5$ is indicative of secondary energy source, $EYR < 2$ indicates consumer products or transformation steps (Brown and Ulgiati, 2002). Processes with $EYR \geq 1$ do not provide significant net emergy to the economy and only transform resources that are already available from previous processes (Dong et al., 2008).
$EIR = \frac{F}{N+R}$	The investment ratio is the ratio of purchased inputs ( $F$ ) to all emergies derived from local sources ( $R + N$ ). EIR indicates the matching of emergy inflows to production, which is equivalent to balance potential limiting factors.	For an $EIR = 1$ the system is limited by only the external sources. For $EIR > 1$ , the uneven emergy matching increases production, but local resources may be less efficiently used. $EIR < 1$ indicates that the process gets more emergy from the environment and is less intensive (Odum, 1996).
$ELR = \frac{N+F}{R}$	This index of environmental loading is the ratio of non-renewable emergy ( $N + F$ ) to renewable emergy.	$ELR \approx 2$ suggests a relatively low environmental impact. $ELR > 10$ is indicative of relatively concentrated environmental impact and those with $3 < ELR < 10$ might be considered moderate (Brown and Ulgiati, 2002).
$ESI = \frac{EYR}{ELR}$	The environmental sustainability index aggregates the measure of yield and environmental loading. The objective function for sustainability is to obtain the highest yield ratio at the lowest environmental loading.	As a relative measure, $ESI < 1$ appears to be indicative of products or processes that are not sustainable in the long run. Medium run sustainability seems to be characterized by $1 < ESI < 5$ , while processes and products with long range sustainability have ESI accordingly greater (Brown and Ulgiati, 2002).
$EER = \frac{U_{coffee}}{(\$_{paid})(EMR)}$	The ratio of emergy exchange in a trade or purchase. EER gives the extent of the relative trade advantage of one partner over another.	$EER = 1$ indicates a fair trade; $EER > 1$ indicates advantage of the buyer and $EER < 1$ , advantage of the seller (Odum, 1996).
$EMR = \frac{U_{country}}{GDP}$	The ratio of all emergy supporting the economy of a country ( $U_{country}$ ) to its gross domestic product (GDP).	EMR provides an average measure of the purchasing power for a nation when compared with ratios from other nations (Odum, 1996).

**Table 2**  
Energy Money Ratio (EMR) and the gross domestic product (GDP) percentage relative to coffee exports from 1999 to 2004.

	EMR <sup>a</sup> ( $10^{12} \times \text{sej}/\$$ )	% GDP						Weighted EMR per country <sup>b</sup> ( $10^{12} \times \text{sej}/\$$ )	% GDP per country 1999–2004
		1999	2000	2001	2002	2003	2004		
Belgium	9.17	0.22	0.14	0.11	0.10	0.07	0.09	6.69	0.73
Germany	2.8	0.93	0.49	0.41	0.44	0.34	0.38	8.37	2.99
Italy	3.85	0.40	0.32	0.23	0.19	0.21	0.19	5.93	1.54
Japan	1.49	0.38	0.28	0.18	0.15	0.16	0.14	1.92	1.29
USA	1.93	0.98	0.40	0.25	0.34	0.35	0.33	5.11	2.65
<b>Total</b>								<b>28.03</b>	

<sup>a</sup> EMR values were taken from NEAD (2009) for the year 2000.

<sup>b</sup> The weighted EMR of the importing countries is calculated by dividing the total weighted EMR by the total % GDP of coffee exports.

### 3. Results and discussion

#### 3.1. Description of Santo Inácio farm's production system in energy terms

The Santo Inácio coffee farm is located at Coromandel in the Cerrado region, and produces green coffee exclusively for export. The coffee farm has a total area of 140 ha, of which 54 ha are planted with 160,000 coffee trees (*Coffea arabica* L.). Council of Associations of Cerrado's Coffee Growers (CACCER, 2010) classifies this farm as a small property as it has less than 79 ha of plantation.

Coffee production data (Table 3) were obtained from Santo Inácio's account book for the period between 1997 and 2006. The cultivation of coffee started in 1970, and the first harvesting was done in 1973. Coffee bushes are grown in alleys in this conventional coffee production system. After harvesting, the coffee cherries are dried and their husk is removed (pre-processing). The final product is green coffee, which is packed in 60 kg bags and stored in a Cooperative of Producers for future trade.

Fig. 1 presents an overview of the coffee production area using energy system symbols. The diagram shows the system

boundaries and the energy sources driving the process. On the left-hand side of the diagram environmental resources are shown. Purchased resources such as fuel and electricity, chemicals, labor and machinery are shown on the top of the diagram. Each processing step was evaluated and indicated in Table 3.

The environmental accounting was performed from 1997 to 2006, enabling the evaluation of environmental and economic resources employed in the system over ten years. Table 3 shows the emergy table corresponding to the year of 2006. The other evaluation tables are available on request.

For the green coffee production system (Table 3), the purchased inputs contributed with almost 80% of the total emergy. Fuel contributes with 8%, direct labor with 25% and chemical fertilizers with 29% to the emergy support required. Local renewable emergy accounted for ca. 20% of the total emergy needed for producing green coffee. The transformity calculated without services for the green coffee was  $2.42 \times 10^5 \text{ sej}/\text{J}$ , which is about three times lower than that reported for Nicaragua ( $7.11 \times 10^5 \text{ sej}/\text{J}$ , Cuadra and Rydberg, 2006) suggesting that coffee production in the Brazilian farm is more efficient.

The total amount of emergy at the plantation stage corresponds to 2/3 of the emergy required to put the green coffee at

**Table 3**  
Emergy table for the coffee production in Santo Inácio farm, 2006 (without services).

Item	Description	Unit	Class <sup>a</sup>	Annual flow (unit/year ha)	Emergy per unit (sej/unit) <sup>b</sup>	Emergy (sej/year ha)
<b>Plantation</b>						
1	Sun <sup>c</sup>	J	R	$5.97 \times 10^{13}$	1	$5.97 \times 10^{13}$
2	Wind, kinetic energy <sup>c</sup>	J	R	$6.45 \times 10^6$	$2.52 \times 10^3$	$1.63 \times 10^{10}$
3	Rain, chemical energy	J	R	$4.27 \times 10^{10}$	$3.06 \times 10^4$	$1.31 \times 10^{15}$
4	Rain, geopotential energy <sup>c</sup>	J	R	$8.21 \times 10^6$	$1.76 \times 10^4$	$1.44 \times 10^{11}$
5	Organic fertilizer	J	29% R	$2.72 \times 10^4$	$2.96 \times 10^9$	$8.05 \times 10^{13}$
6	Soil erosion	J	N	$9.95 \times 10^7$	$7.40 \times 10^4$	$7.36 \times 10^{12}$
7	Fuel and lubricants	J	F	$1.67 \times 10^9$	$1.11 \times 10^5$	$1.85 \times 10^{14}$
8	Machinery and equipment	g	F	$1.61 \times 10^4$	$6.70 \times 10^9$	$1.08 \times 10^{14}$
9	Labor <sup>d</sup>	J	F	$1.85 \times 10^8$	$4.30 \times 10^6$	$7.96 \times 10^{14}$
10	Lime	g	F	$7.41 \times 10^4$	$1.68 \times 10^9$	$1.24 \times 10^{14}$
11	Pesticides and fungicides	g	F	$3.08 \times 10^3$	$1.48 \times 10^{10}$	$4.56 \times 10^{13}$
12	Nitrogen	g	F	$1.65 \times 10^5$	$6.62 \times 10^9$	$1.09 \times 10^{15}$
13	Phosphate	g	F	$7.14 \times 10^4$	$9.35 \times 10^9$	$6.68 \times 10^{14}$
14	Potassium	g	F	$1.21 \times 10^5$	$9.32 \times 10^8$	$1.13 \times 10^{14}$
15	Organic fertilizer	g	71% F	$6.35 \times 10^4$	$2.96 \times 10^9$	$1.88 \times 10^{14}$
<b>Total for plantation</b>						<b><math>4.71 \times 10^{15}</math></b>
<b>Harvesting</b>						
16	Fuel and lubricants	J	F	$2.92 \times 10^9$	$1.11 \times 10^5$	$3.24 \times 10^{14}$
17	Machinery and equipment	g	F	$1.80 \times 10^4$	$6.70 \times 10^9$	$1.21 \times 10^{14}$
18	Labor <sup>d</sup>	J	F	$1.99 \times 10^8$	$4.30 \times 10^6$	$8.56 \times 10^{14}$
19	Lodging for temporary workers	g	F	$2.68 \times 10^5$	$2.42 \times 10^9$	$6.49 \times 10^{14}$
<b>Total for harvesting</b>						<b><math>1.95 \times 10^{15}</math></b>
<b>Drying</b>						
20	Sun <sup>c</sup>	J	R	$1.29 \times 10^{11}$	1	$1.29 \times 10^{11}$
21	Wind, kinetic energy	J	R	$1.12 \times 10^8$	$3.06 \times 10^4$	$3.43 \times 10^{12}$
22	Evaporation <sup>c</sup>	g	R	$5.56 \times 10^5$	$1.45 \times 10^5$	$8.06 \times 10^{10}$
23	Electricity	J	F	$7.73 \times 10^7$	$2.77 \times 10^5$	$2.14 \times 10^{13}$
24	Yard	g	F	$3.33 \times 10^4$	$2.42 \times 10^9$	$8.06 \times 10^{13}$
25	Silos	g	F	$4.83 \times 10^4$	$2.42 \times 10^9$	$1.17 \times 10^{14}$
26	Machinery and equipment	g	F	$7.67 \times 10^3$	$6.70 \times 10^9$	$5.14 \times 10^{13}$
27	Labor <sup>d</sup>	J	F	$2.05 \times 10^7$	$4.30 \times 10^6$	$8.82 \times 10^{13}$
<b>Total for drying</b>						<b><math>3.62 \times 10^{14}</math></b>
<b>Pre-processing</b>						
28	Machinery and equipment	g	F	$8.89 \times 10^2$	$6.70 \times 10^9$	$5.96 \times 10^{12}$
29	Labor <sup>d</sup>	J	F	$6.30 \times 10^6$	$4.30 \times 10^6$	$2.71 \times 10^{13}$
30	Fuel	J	F	$4.92 \times 10^8$	$1.11 \times 10^5$	$5.46 \times 10^{13}$
31	Jute bags	g	F	$7.72 \times 10^1$	$2.31 \times 10^{10}$	$1.78 \times 10^{12}$
32	Electricity	g	F	$5.73 \times 10^7$	$2.77 \times 10^5$	$1.59 \times 10^{13}$
<b>Total for pre-processing</b>						<b><math>1.05 \times 10^{14}</math></b>
<b>Total Emergy without services</b>		kg		$1.20 \times 10^3$	$5.94 \times 10^{12}$	<b><math>7.13 \times 10^{15}</math></b>

<sup>a</sup> R: local/free renewable resource, N: local/free non-renewable resource, F: feedback from the economy or purchased resources.

<sup>b</sup> Emergies per unit for items 1–7, 23 and 30 were taken from Odum (1996); for items 8, 17, 26 and 28 from Bjorklund et al. (2001); for item 10 from Brown and Buranakarn (2003); for item 11 from Panzieri et al. (2000); for items 12–14, 19, 24 and 25 from Cuadra and Rydberg (2006); for item 22 from Buenfil (2001); and for item 31 from (Brandt-Williams (2002).

<sup>c</sup> Not accounted to avoid double-counting.

<sup>d</sup> Brazil's total emergy ( $2.77 \times 10^{24}$  sej/year)/( $1.80 \times 10^8$  person/day  $\times$   $1.26 \times 10^7$  J/person  $\times$  285 days, excluding Sundays and holidays); Bonilla et al., 2010.

the farm gate. The emergy cost of the harvesting stage corresponds to 27% of the total emergy, and direct labor force is responsible for 12% of the emergy required at this stage. Drying uses nature's free resources (sun, kinetic energy of wind and evaporation), but their contributions to the total emergy are negligible. No direct renewable emergy flows were identified in the preprocessing stage, which contributes with less than 1% to the total emergy demand for green coffee production.

Inputs purchased from outside the system have two constituent parts, and as separate sources must be evaluated separately (Odum, 1996). The first component refers to the emergy of the materials and direct labor (accounted in Table 3). The second corresponds to the emergy that supports human services, which may be inferred from the price of imported items multiplied by the Emergy Money Ratio of the economy in which the system is inserted. According to Brown and Ulgiati (2002), emergy values calculated without services are associated to the physical and technological characteristics of the system under investigation,

while components that depend on indirect labor and services will vary according to the economic level of the country in which the system operates.

Table 4 shows the services associated to the imported materials and the indirect human services of the farm, measured by their money costs. Variable costs (item 3) were obtained by adding the prices of organic fertilizers, fuel and lubricants, lime, pesticides, herbicides, and chemical fertilizers (CONAB, 2009; CCAC, 2006). Fixed costs include machinery, equipments, buildings and facilities (CONAB, 2009; CCAC, 2006).

Brazilian's green coffee transformity with services ( $4.25 \times 10^5$  sej/J) is about four times lower that of Nicaragua ( $1.77 \times 10^6$  sej/J, Cuadra and Rydberg, 2006), where services associated to green coffee production increase the total emergy by 67%. The inclusion of the emergy associated to services and indirect labor increases the Brazilian green coffee transformity by 43%. Transformities, with and without services, suggest that the coffee production in the Brazilian farm is more efficient, but these

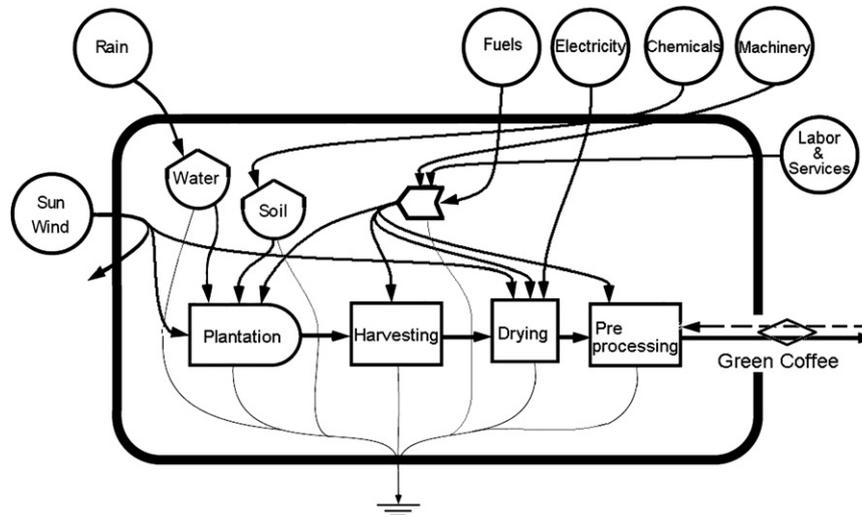


Fig. 1. System diagram of coffee production at Santo Inácio farm. The emergy evaluation is performed for production, harvesting, drying, and preprocessing stages.

**Table 4**  
Emergy of services for the coffee production in Santo Inácio farm, 2006, calculated with the Brazilian EMR =  $1.12 \times 10^{13}$  sej/\$, 2000 (NEAD, 2009).

Item	Description	Annual flow (\$/year ha)	Emergy (sej/year ha)
<b>Labor</b>			
1	Farm management/consulting services	$8.35 \times 10^1$	$9.35 \times 10^{14}$
<b>Services</b>			
2	Variable costs	$1.33 \times 10^2$	$1.49 \times 10^{15}$
3	Fixed costs	$2.65 \times 10^2$	$2.97 \times 10^{15}$
<b>Total services</b>		$4.82 \times 10^2$	$5.39 \times 10^{15}$
<b>Total emergy without services<sup>a</sup></b>			$7.13 \times 10^{15}$
<b>Total emergy with services</b>		$1.20 \times 10^3$	$1.25 \times 10^{16}$

<sup>a</sup> Table 3.

**Table 5**  
Environmental performance indicators of green coffee production in Brazil and Nicaragua.

Emergy-based environmental performance indicators	Without services		With services	
	Brazil	Nicaragua	Brazil	Nicaragua
EYR	1.24	1.35	1.13	1.12
ELR	4.13	2.82	8.01	8.52
EIR	0.24	0.35	0.13	0.12
ESI	0.30	0.38	0.14	0.13

values are only sensitive to the biosphere-scale efficiency (Dong et al., 2008), and do not provide information about the system's environmental performance.

Table 5 shows the environmental performance indicators of green production in Brazil and Nicaragua, with and without accounting for the emergy content of indirect labor and services.

Emergy-based performance indicators respond to the characteristics of input flows, and the values shown in Table 5 make clear the influence of the economic level of each country. In respect to the physical and technological characteristics the Brazilian farm presents a poorer environmental performance, especially associated to its environmental load. When the fraction depending on indirect labor and services is taken into account, the Brazilian environmental performance indicators are slightly

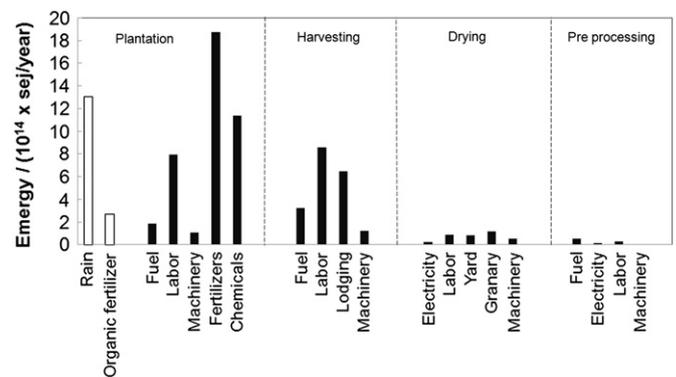


Fig. 2. Emergy inputs per stage (emergy signature) of the coffee production at Santo Inácio farm, 2006.

better. However, this occurs at the expenses of a larger environmental disruption.

It is also worthy to keep in mind that emergy flows of indirect labor and services may be divided into their renewable and nonrenewable fractions, since they are supported by their own economic system, and vary in alignment with them (Dong et al., 2008). Labor and services are 50% renewable both in Brazil and Nicaragua (NEAD, 2009), which makes possible this evaluation. However, comparisons made with another coffee producers as Colombia (%R=61) or Costa Rica (%R=37) would have to take into account the renewable fraction of each country.

### 3.2. Assessment of the energy flows driving the production process and of the emergy indices as function of the green coffee productivity

Fig. 2 shows the main input emergy flows to the different steps of the coffee production at the Santo Inácio farm. It is clear that the largest share of emergy is used in the plantation stage, in which 28% of the emergy comes from a renewable source, 2% sej/sej from organic fertilizers, and the remaining portion comes from outside sources. Most energy transformations are controlled by inputs of high transformity, whose energy contribution is small but whose energy contribution is large. Fertilizers (NPK) and chemicals (pesticides and lime) contribute with 45% of the emergy at this stage, which corresponds to 31% of the total emergy. Harvesting is the second in emergy use. In this phase, labor corresponds to 44% of the emergy investment, followed by the emergy invested (33% sej/sej)

to accommodate temporary workers, and by the fuel used by harvesting machines (17% seJ/seJ). Drying and pre-processing phases use less than 7% of the total energy used for green coffee production.

A summary of the indices calculated for the different steps in green coffee production is presented in Fig. 3. The percentage of renewables decreases along the production chain, with coffee production in the field showing the highest values (28% seJ/seJ) and after pre-processing the lowest value (19% seJ/seJ). EYR and ESI decrease along the coffee production stages. In contrast, the environmental loading ratio (ELR) and the energy investment ratio (EIR) increase for each processing step.

As expected, the production of green coffee is an intensive activity, requiring large amounts of inputs from outside. This

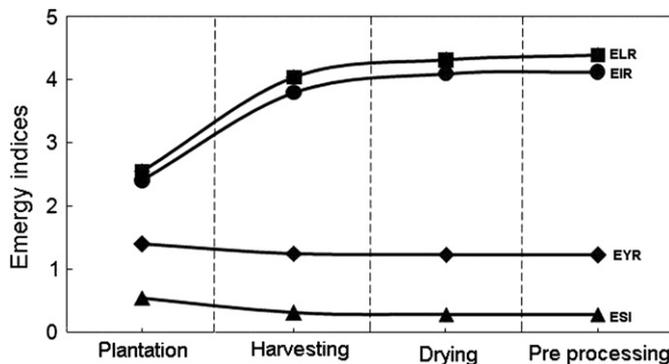


Fig. 3. Variation of energy indices for green coffee production from plantation to pre-processing, 2006.

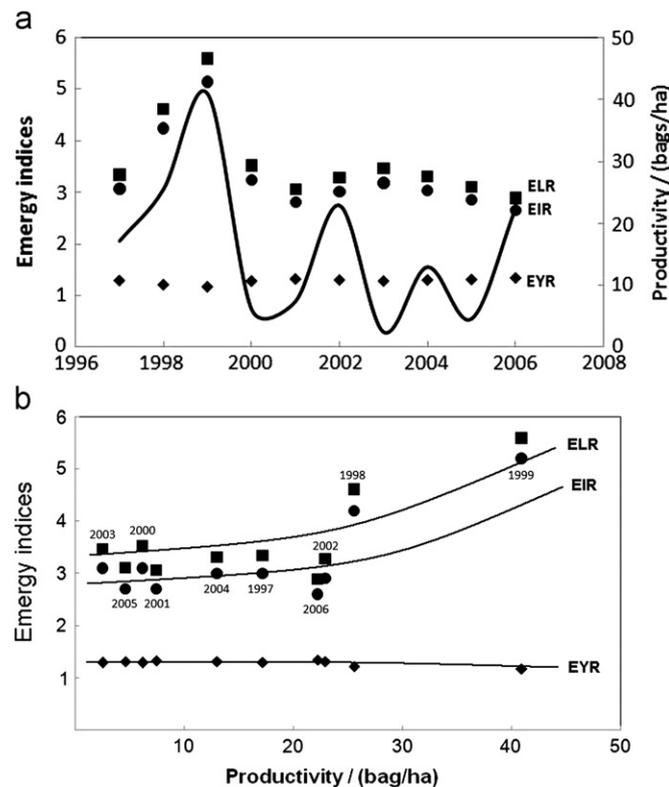


Fig. 4. (a) Variation of the energy indices from 1997 to 2006. The black line represents the productivity variation along the years; where: Energy Yield Ratio (EYR); Energy Investment Ratio (EIR); and Environmental Load Ratio (ELR). (b) Energy indices as function of Santo Inácio farm productivity. Production is accounted in bags of coffee of 60 kg; where Energy Yield Ratio (EYR); Energy Investment Ratio (EIR); and Environmental Load Ratio (ELR).

intensity was demonstrated by the high ELR obtained for each stage. ESI is lower than one for all stages indicating that the coffee production system has short-run resource-use sustainability, depending on a large quantity of non-renewable sources.

Indices calculated for the different years of coffee production are presented in Fig. 4a and b. In 1997, the farm produced 17 coffee bags/ha with EYR=1.33. Coffee production increased to 26 bags/ha in 1998 and 41 bags/ha in 1999, but the higher productivity was achieved by the intensive use of chemical fertilizers. Each time that the energy for transformation is being supplied by the economy, the energy yield ratio decreases. Thus, in Santo Inácio farm, the value of energy yield ratio for 1999 (EYR=1.17) decreased about 10% in relation to the EYR from 1997 (1.30) showing a decreased ability to exploit local resources. This trend may be better observed in Fig. 4b where the variation of the energy indices is shown as function of the farm productivity. The energy investment (EIR) is also higher for 1999 indicating the intensity of the economic investment in fertilizers. Comparing 1997 and 1999, it is clear that the environmental load ratio (ELR) increased from 3.3 to 5.6 indicating the higher pressure exerted by the system to the environment. A high ELR indicates the system's distance from the state of environmental equilibrium, and a high dependency or a high degree of support from outside. This is observed for the year of 1999 when more than 80% of the total energy was provided by resources from outside the system.

Fig. 4a and b shows that the higher productivity achieved with the energy investment based on economic resources (mostly fertilizers) do not provide significant net energy to the economy.

### 3.3. Determination of the optimum production model combining productivity and environmental performance

According to Odum (1996), if one evaluates the transformity of processes that have not been running long enough to develop their maximum efficiency for full sustainable production, a higher transformity (or lower efficiency) may be found. Later, after the system is operating at the highest output possible the transformity calculated should be lower (or the efficiency higher). In natural systems, through trial, error and selection, transformities reach the theoretical lower limit (corresponding to the most efficient possible system) reflecting the thermodynamic limits of energy transformation in open systems (Odum, 1996). On the other hand, coffee production is a man-made system, driven by market demands and depending on different feedback loadings on the production process. The contrast between ESI and the transformity may provide an insight to determine the number of coffee bags to be produced by Santo Inácio farm in order to achieve the lowest transformity and the highest ESI (Fig. 5).

The analysis of Fig. 5 shows that there is an optimum interval for coffee production at Santo Inácio farm ( $10 < \text{coffee bags/ha} < 25$ ),

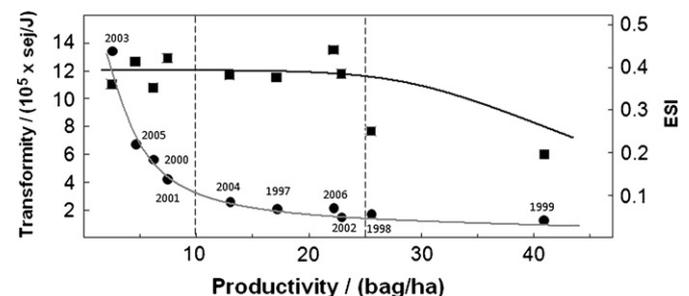


Fig. 5. Transformity (●) and ESI (■) as function of coffee bags produced in Santo Inácio coffee farm from 1997 to 2006.

where transformity is low and the environmental performance (ESI) is maximized. If the quantity of coffee bags is lower than 10 bags/ha (2000, 2001, 2003 and 2005), the ESI and the transformity are high, indicating high sustainability, but low efficiency. For the point corresponding to 1999, the efficiency is high, but the sustainability index is the lowest of all ten years. Thus, according to this data, Santo Inácio farm should produce approximately 20 bags of green coffee per hectare to accomplish its best performance regarding both the production efficiency and the environment.

Energy indices are highly dependent on the quality of the energy fluxes that enter the system, but also on the balance among these fluxes. In Fig. 6 (columns), renewable resources and resources from outside the system are shown as percentage terms of the total energy for each year studied. The quantity of coffee bags produced per hectare (right axis) for each year is represented by the line/symbol graphic, showing also that coffee trees production cycle takes about two or three years (Wintgens, 2009). The ratio R/F does not vary significantly along the years and, for all years chemical fertilizers and labor are the most important economic resources used for green coffee production. Diesel and lubricants contribute with 3–9% to the total emergy. The higher use of chemical fertilizers in 1998 and 1999 increased the productivity in these years. From 2000 to 2006, the labor component increased, but productivity was lower.

When these results are examined considering the emergy indices obtained for each year, it is easy to understand that the higher use of chemical fertilizers in 1998 and 1999 increases the productivity, but brings down the indices' values. Despite of the R/F ratio being almost constant, when the labor component increases (2000–2006), indices have better values indicating that, from the biosphere's point of view, it should be preferable to invest in a production model that optimizes the use of fertilizers,

even if it is necessary to use more labor. In fact, organic production systems were already proposed as an alternative for small producers because of the ability of this agricultural production model of using free natural inputs instead of purchased chemicals (Sarcinelli and Ortega, 2004). In this case, one may add that the balance among the driving energy fluxes may also improve the environmental performance of agricultural systems.

It is also worthy to mention that the increasing need for labor can bring a social benefit, provided that the appropriate training is available and that the coffee farmers are encouraged to improve working conditions. This model may become more attractive to producers as work, and not chemical fertilizers, becomes a significant portion of their inputs reducing producers' dependence on imported products and technologies, and generating local social well-being and valorizing human capital.

### 3.4. Determination of the optimum production model combining sales and environmental performance

All the green coffee produced in the farm is exported. Sales are usually done between harvests, in the months of March and April, with the aim of optimizing the coffee price.

Fig. 7 shows the emergy exchange ratio (EER) for trading to the bloc formed by USA, Germany, Italy, Japan and Belgium (left axis). The value of EER=1, represents the equity where there is no benefit economically and environmentally favorable to the producer or the buyer. In the years of 1998, 1999 and 2004 points are below the line EER=1 and this was achieved by combining high productivity and good market prices. But, in 2004, when less fertilizer was used, the ESI is higher. Thus, the best production arrangement was achieved in this year. In the remaining years, the emergy exchange ratio reveals that purchasers generally benefit when buying green coffee from Santo Inácio farm. This means that the farm exports much more energy in the green coffee sold than that contained in the money received for the coffee.

In 2001, ESI is high, but the value of EER=2.69 indicates that in this year the farm exported nearly three times more energy for buyers than that associated to the money received as payment. In this year the productivity was very low (7 bags/ha) and the market price was also low (US\$ 80/bag) compared with the average market price for the ten years studied (US\$ 120/bag). Similar results were obtained for 2000, 2003 and 2005. Results of 1998 and 1999 show that it is possible to procure a fair price for the green coffee sales establishing a relationship between the quantities sold and the market price, but in these years the higher productivity was achieved increasing fertilizers quantities, and ESI was lower. For the years 1997, 1998 and 2006, a good environmental performance was achieved, but the farm exported

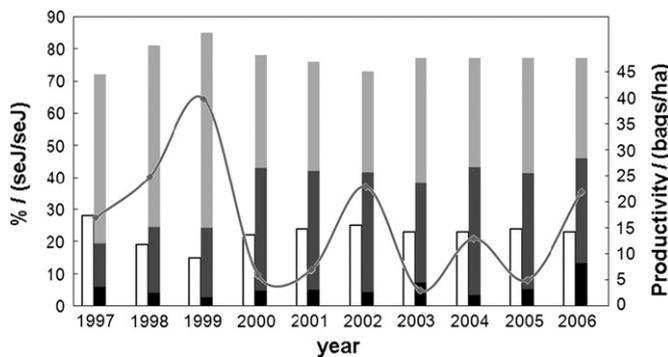


Fig. 6. In the left axis: percentages of renewable (□) and non-renewable resources used in Santo Inácio farm from 1997 to 2006, where (■) refers to fuels, (■) refers to labor and (■) to the percentage of fertilizers. In the right axis the variation of productivity in bags of 60 kg (—■—) is shown for each year.

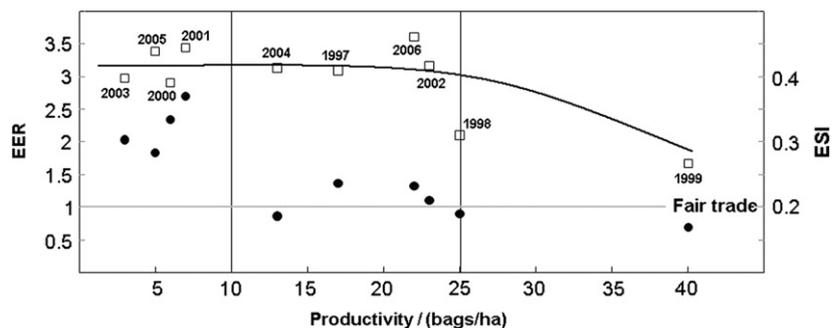


Fig. 7. In the left axis (●), the emergy exchange ratio (EER) of Santo Inácio farm exportations from 1997 to 2006. The average EER for the period is 1.51. In the right axis (□), the environmental sustainability indices for each year.

more energy than that received from buyers due to the low market prices in this period.

These results confirm and complement those obtained by contrasting productivity and environmental performance. Despite of the market prices variation, the optimum interval for Santo Inácio's farm is between 10 and 25 coffee bags/ha.

#### 4. Conclusions

Coffee production in Brazilian savannah (Cerrado) was evaluated using emergy synthesis in order to assess the energy flows that support green coffee production.

It was observed that for each year, the percent renewable (%R) decreased with the processing of coffee, with coffee production in the field showing the highest values (28% seJ/seJ) and pre-processed coffee the lowest values (19%). In contrast, the environmental loading ratio (ELR) and the emergy investment ratio (EIR) increased for each processing step, with coffee cherries showing the lowest value (2.40), and pre-processed coffee the highest value (4.12). Despite the relatively high use of renewable resources, the plantation phase uses also the highest quantities of resources that come from outside the system, chemical fertilizers and labor being the most important economic resources for coffee production. Diesel and lubricants contribute with less than 10% of the total emergy.

Emergy indices can evaluate coffee production and its relation with the environment, and are indicators of the balance in trade to achieve the best environmental performance combined with the highest local productivity. The assessment of emergy indices as function of the farm's productivity indicated that the higher use of fertilizers increases the local productivity, jeopardizing the global sustainability. When the production is higher than 25 bags/ha trade is not favorable to the environment and ESI is low. In contrast, when coffee production is lower than 10 bags/ha, trade is not favorable to the coffee producer, as the ESI is high but the production efficiency is low. An optimum interval for coffee production at Santo Inácio farm ( $10 < \text{coffee bags/ha} < 25$ ) was proposed in order to maximize the efficiency of resource use and the environmental performance. This option implies that the farm should decrease the use of fertilizers, which is the main emergy input, choosing a production model similar to that used to produce high quality organic coffee. High quality coffee uses more labor, but less fertilizer. This means more employment and lower stress to the environment. The same interval was also found as the best for green coffee sales. Even in years in which market prices were not favorable, the quantity of emergy exported to buyers, without payment was lower than that observed for the years with productivity below 10 bags/ha.

Emergy synthesis clearly appears to be a powerful tool not only for the evaluation, but also for planning and managing production systems. Results on the environment/productivity trade-off found for the coffee production suggest that a similar trade may occur in other agricultural and non agricultural systems. This means that the study of the relationship between the environmental performance and productivity of any product, using emergy synthesis, can be useful to determine the best production model for any production system.

#### Acknowledgments

The authors thank Mr. Mario Massao Kuwabara, owner of St. Inácio Farm who was a major contributor to this work, and his manager, Mr. Gervânio Luis Pereira, for data supplied and friendly cooperation. This study had financial support from Vice-Reitoria de Pós-Graduação e Pesquisa da Universidade Paulista.

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