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Sustainability assessment of a giant bamboo plantation in Brazil: exploring the influence of labour, time and space

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ABSTRACT

Bamboo presents physical and mechanical characteristics, which turn it an alternative option for product development, replacing native or reforested wood. The sustainability assessment of a *Dendrocalamus Giganteus* species plantation in Brazil through the emergy methodology evidences a great weight of renewable (30% sej/sej) and human labour contributions (33% sej/sej). These contributions account for the great interface with environment and to the intensive work, respectively. The transformity value of bamboo production is 2.42E + 04 sej/J. The influence human labour has on the total emergy flow and on indicators is evaluated by taking into account different country locations (Brazil, Australia and China). Thus, a different transformity value for labour is assumed for each country. A ranking based on emergy sustainability index (ESI) values shows that bamboo production in China was the first placed, followed by Brazil and Australia (values of 1.18, 0.50 and 0.09, respectively). The insertion of indirect renewability embedded in labour results in the ranking modification, leading to plantation in Brazil in the first place, followed by the Australian and Chinese ones. The relative position of the bamboo systems is visualized in the ternary diagram expressed in terms of emergy. In an attempt to explore the relationship between sustainability and time, a graphic of ESI vs. global productivity is discussed in terms of a prospective evaluation. Indirect support areas of the bamboo production are calculated as a way to evaluate the sustainability-space relationship.

1. Introduction

With the increasing deforestation and pressure against the tropical forests as well as against reforestation areas, it is becoming more necessary to opt for renewable materials and more sustainable processes.

The bamboo, having the property of rapidly sequestering the atmospheric carbon, also presents excellent physical and mechanical characteristics, which turn it promisingly in product development. These products, such as construction components, pieces of furniture or agricultural tools [1] are developed from culms (the aerial axis emerging from buds of the subterranean system, divided into nodes and internodes) and represent an alternative substituting native or reforested wood in some industrial applications. In this way, as far as strength is concerned bamboo is better than timber (and also than concrete) [2]. In terms of stiffness, the first place is for bamboo when compared not only with timber but also with steel and concrete [2].

The emergy environmental accounting [3] can be used to evaluate the sustainability of the bamboo production system since it involves resources from environment and economy. The emergy analysis enables to account for the natural and economic resources, which support a system by using a common metric, expressed in solar emergy joule (sej). For this purpose, every input or resource that enters the system is not only quantified but also classified in *R*, *N* or *F* (renewable, non-renewable and purchased, respectively) according to its characteristic.

Emergy contribution of human labour can represent a high parcel of total flow depending on the intrinsic characteristic of systems (for example those processes which employ human labour in an intensive way) and on the high hierarchical level of human services (represented by a larger transformity value). Even so, transformity values assigned to human labour could vary depending on the criteria adopted by the analyst and/or the aspect taken into account. In this way, human labour could represent national, regional or local aspects, or be calculated under a micro or macroeconomic approach and, depending on the objective of the assessment, transformity assignment will be different. In order to strengthen the argument, results of emergy flows of some crops in

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Florida [4] are depicted in Appendix A in order to show how transformity selection could substantially change the weight of human labour in the total emergy. Emergy for human labour was calculated at the original reference by considering migrant workers. The emergy contribution corresponding to human labour attained 16% (sej/sej) depending on the crop. In the present work transformity is calculated from the emergy use per person taking into account the total emergy availability of a country. When the same criteria adopted in the present work were used and emergy flows recalculated for Florida data [4], human labour contribution attained values within 8 and 92% (sej/sej) (results shown in Appendix A).

In this way, countries with higher emergy values reflect a good availability of resources, technical background and/or natural reserves, although relative distribution of renewable, non-renewable and purchased flows usually varies among countries even for similar total values. In this way, considering that each human being profits for a determined parcel of the emergy stock of a country, his own parcel should reflect the same distribution of resources of the whole country. Going further and always within a macroeconomic approach, the input flows which support human labour in the production systems are constrained by the emergy distribution of the country. Although the contribution of the renewable fraction embedded in the input flows usually becomes unrecognizable as the analyzer displaces from the primary sources, the inclusion of the embedded % of R in the calculus should lead to more realistic results [5]. Some authors have already adopted the procedure of including the indirect renewability of diverse input resources that do not present an apparent and direct R content [6–10].

The relative proportion of each type of input resources involved in an emergy system evaluation as well as the interaction between system and environment can be graphically represented and easily visualized in the ternary diagram, proposed by Giannetti et al. [11]. The tool can be employed to assist in the decision making process, since it jointly carries the theoretical support and the easy handling. The diagram has shown usefulness when employed in the study of several productive processes [10–12].

The aim of the present work is to analyze all the resources (natural and purchased) employed in a *Dendrocalamus Giganteus* bamboo plantation directed to culms production placed in Bauru (São Paulo State, Brazil) by using the emergy assessment. The influence of labour on the total emergy flow as well as on the emergy indices is evaluated by comparing with the results from the bamboo plantation in two other country locations. The countries selected for the simulation were chosen considering on one side the major bamboo producer, China and on the other side, Australia since well-directed projects are being carried out in that country in order to develop bamboo production [13]. The major emergy flows were identified and the ternary diagram was used in order to visualize the relative position of the systems when labour of the different countries was simulated. The influence of the relative proportion of renewable flows (%R) embedded within labour for each country was also explored and results were compared. An exploratory discussion on sustainability and its relationships with time and space is also presented. The influence of time is discussed in terms of the capacity for the environment to guarantee the supplement of the necessary resources to the systems. The influence of space is evaluated by the calculation of the indirect area used by the systems to guarantee the supply of resources.

2. Methodology

2.1. Emergy environmental accounting

Emergy accounting methodology [3] was developed over the last four decades as a tool for environmental policy and to evaluate the quality of resources in the dynamics of complex systems. A complete assessment of the methodology cannot be provided here, but the reader may refer to published reports [3,14].

Briefly, emergy is defined as the sum of all inputs of energy directly or indirectly required by a process to provide a given product when inputs are expressed in the same form (or type) of energy, usually solar energy [3].

The emergy flows represent three categories of resources: R as renewable resources, N as non-renewable resources and the inputs provided by the economy, F. All three categories are fundamental for the emergy accounting and for the understanding of the system interactions with the environment. R and N flows are provided by the environment and are economically free.

While renewable resources can be replaced at least at the same rate as they are consumed, the non-renewable resources are depleted faster than their ability of recuperation. The economic inputs, F, are provided by the market and are related to flows supplied by the economy. The emergy employed to obtain the product, Y (defined as $Y = R + N + F$), may include products, services and also emissions that are released to the environment.

In order to establish the emergy flows, every mass, energy or monetary input has to be inventoried and multiplied by its correspondent transformity or emergy/unit value. The identification of the flows by the emergy environmental accounting enables the calculation of emergy indices. Only a brief description of the indices is provided here but complete information can be found in Odum [3] and in Brown and Ulgiati [14].

The emergy yield ratio, EYR is defined as the ratio of the inputs divided by the purchased inputs ($\mathrm{EYR} = Y/F$). The emergy investment ratio, EIR is defined as the ratio of purchased inputs divided by the local resources ($\mathrm{EIR} = F/(R + N)$). The index of emergy loading ratio, ELR is the ratio of purchased and non-renewable inputs divided by the renewable inputs ($\mathrm{ELR} = (N + F)/R$). The emergy sustainability index, ESI aggregates the measure of emergy yield ratio and emergy loading ratio and is defined as the ratio of the emergy yield ratio and the emergy loading ratio ($\mathrm{ESI} = \mathrm{EYS}/\mathrm{ELR}$). Indices are recalculated by considering the renewable portion of the human labour flow, accordingly to the renewable input available for a given country.

Labour transformity selection was unified in order to avoid divergences due to other factors rather than differences among systems. It is well known that different analyst's criteria have an important influence on emergy results. In this way, a same source of the necessary data to calculate transformity for national labour for the three countries (Brazil, China and Australia) was chosen [15].

Transformity was calculated for each national labour in a unified way. As an example, Brazilian labour was calculated in Appendix B (Table 5). Transformities calculated for the three countries are listed in Table 6 of Appendix B.

2.2. Introducing the system: giant bamboo production in Brazil

The plantation area covers about 2500 m^2 in extent where *Dendrocalamus Giganteus* bamboo species are cultivated (“Bamboo Project”, developed by the Mechanical Department, UNESP). This plantation area is located in Bauru city, São Paulo State and directed to research devoted to the substitution of traditional wood by bamboo in a good number of utilities. Since 1998 the cultivation yielded mature culms (defined as those with more than 7 years), with adequate dimensions for considering a promising alternative raw material.

The yearly data related to resources employed at bamboo cultivation were field collected and normalized for 1 hectare. Data derived for labour, agricultural machinery and fuel were estimated

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based on a financial inventory already published for bamboo [13]. Lifetime was considered as being 75 years.

2.3. Emergy ternary diagram

Emergy ternary diagrams [11] allow a transparent representation of the emergy accounting results and can act as an interface between emergy researchers and decision makers. The graphic tool produces a triangular plot of three variables with constant sum. The ternary diagram expressed in term of emergy, has three components, R, N and F. These fluxes are represented by an equilateral triangle; each corner represents a flux, and each side a binary system. Points within the triangle represent ternary combinations. In this way, the relative proportions of the elements are represented by the lengths of the perpendicular lines from the given point to the side of the triangle opposite to the considered vertex. Hence, the "composition" of any point plotted on a ternary diagram can be determined by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the vertex of the triangle. These lines are parallel to the triangle sides and are very useful for comparison regarding the use of resources by products or processes (Fig. 1).

The lines related to equi-values of environmental indices enable the immediate verification of the emergetic indices EYR, ELR, EIR and ESI since every point that lies along the line presents the same value (Fig. 2). In the present work only the graphical determination of ESI is illustrated.

For further information on the use and applications of the emergy ternary diagrams see the following papers of Giannetti and co-workers [11,12].

2.4. Indirect area calculation

When it is assumed that all the environmental requirements to support an endeavor are derived from renewable sources, the indirect area defined as the "renewable support area" ($\mathrm{SA}_{(\mathrm{r})}$) [16] is calculated as:

$$\mathrm{SA}_{(\mathrm{r})} = (F + N)/E_{\mathrm{mpd}(r)} \tag{1}$$

where,

$E_{\mathrm{mpd(r)}}$ = renewable empower density of the region (sej/ha year).
F = purchased inputs (sej/ha).
N = non-renewable inputs (sej/ha).

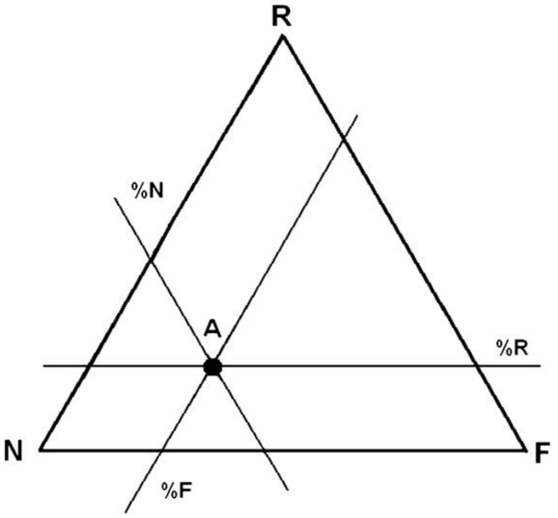

Fig. 1. Representation of a general system A with the relative proportions of R, N and F emergy flows. The sum of % R, % N and % F corresponds to 100%.

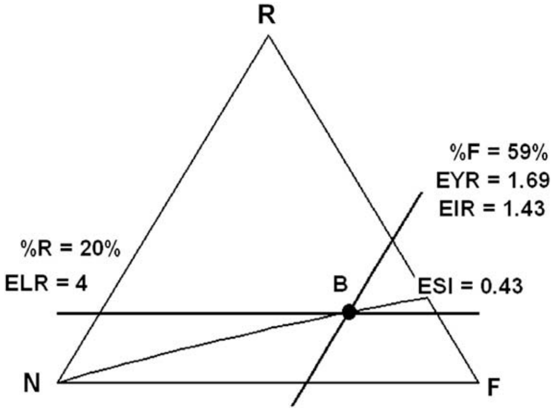

Fig. 2. Representation of a general system B with the lines related to equi-values of the emergy indices.

The area extent will depend on the ability of local environment to provide the necessary resources for the bamboo production on a renewable basis. In this way, the area magnitude will be limited by the flux of renewable emergy that is characteristic of that region.

On the other hand, the support area which corresponds to the area required to balance the proposed development with the ELR of the region, is calculated according to ref. [16] as follows:

$$\mathrm{SA}_{(\mathrm{ELR})} = R^*/E_{\mathrm{mpd}(r)} \tag{2}$$

being $R^* = (F+N)/\mathrm{ELR}_{(\mathrm{r})}$ and representing the value of the renewable flow which matches with the ELR of the region.

where:

$\mathrm{ELR}_{(\mathrm{r})}$ = emergy loading ratio of the region.

The area calculated in this way can be related with a predictor of short-term sustainability whereas the $\mathrm{SA}_{(\mathrm{r})}$ represents a long-term predictor.

3. Results and discussion

3.1. Resources involved in the bamboo production

The energy system flow diagram with the symbols introduced by Odum [3] is represented in Fig. 3. Every resource that enters the system is considered an input to be accounted for. On the left side, the renewable resources supplied by nature are located. The non-renewable and the purchased resources are placed on the left top and on the right top, respectively. Resources are organized from left to right according to increasing transformities.

The total emergy that supports bamboo production is calculated as the sum of free (renewable and non-renewable) and purchased resources contributions. Table 1 constructed from every flow that enters the system, displays the emergy support for the two main steps considered: cultivation and harvest of culms. The emergy inputs from sun, wind and rain are by-products of the same global flow, so only the largest flow was considered in order to avoid double counting.

Since this system operates in a great interface with environment, the high value of direct environmental inputs (rain and geothermic heat) is not surprising, contributing with 25% of the total emergy. It is evidenced how in this kind of system located in the ecological-economic interface, natural resources account for an important portion of the whole emergy.

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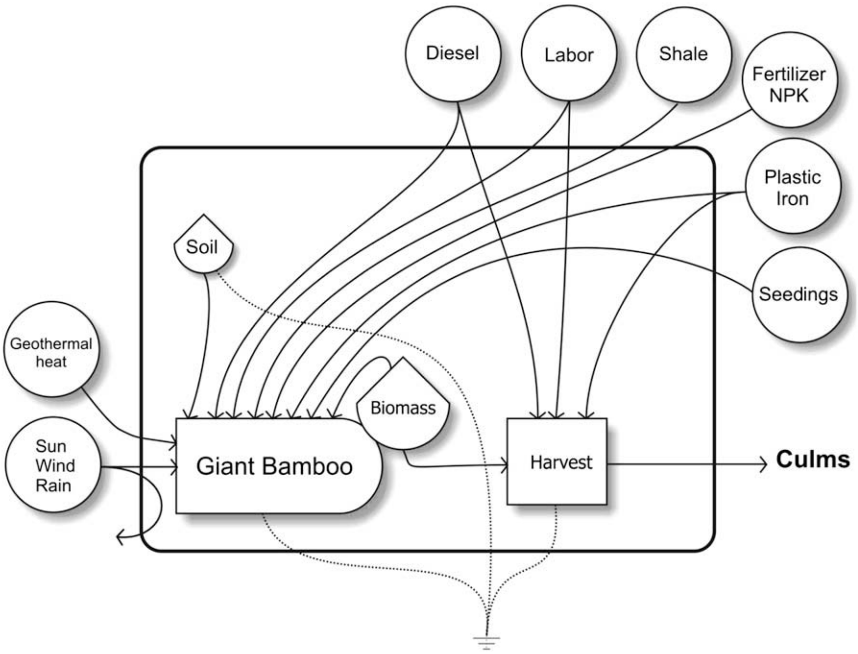

Fig. 3. Energy system diagram of the giant bamboo production system.

On the other hand, the intensive presence of human labour is reflected as the main emergy flow, accounting for 30 and 16% at cultivation and harvest, respectively. Fertilizers and diesel contributed each one to 9% of the total emergy support for culms production. Items 6, 8 and 18 of Table 1 accounted for less than 5% of the total support emergy and represent the yearly parcel of system implantation. It is important to note that the inventory corresponds to the steady state of the system, so the total amount corresponding to the system implantation (not included in the steady state period) was properly allocated and depreciated taking into account that the plantation is considered mature for culms harvest after 7 years [21]. Transformity value is also calculated in Table 1 for bamboo culms production and it accounts for 2.42E + 04 sej/J. No works related to bamboo emergy evaluation were found in literature in order to compare transformity values. The value calculated here has the same order of magnitude of the transformity (3.2E + 04 sej/J) of a rainforest log [3] which was already used for bamboo plantation in Jiang et al. [22].

3.2. Influence of labour on sustainability

According to Table 1, labour is the resource that contributes with more emergy to the system. In this sense, altering the location of the bamboo cultivation, results in drastic sustainability changes as a function of differences in labour transformities among countries. Since the objective is to study the influence of labour, the effect of climatic conditions and soil type is neglected and the same values are maintained in all cases. Labour transformities used for each country are shown in Table 6, Appendix B. Raw flows *R*, *N* and *F* as well as the total emergy, necessary to calculate the indices of each of the six situations, are shown in Table 7, Appendix C.

As shown in the last column of Table 2, the substitution of labour transformity values resulted in an increase of more than 100% of the total emergy for production in Australia when compared to Brazil's. On the other hand, a little decrease of total emergy for the case of China production was observed, due to slight differences between transformity values for Brazilian and for Chinese workers. In this way, since neither changes in the other inputs nor in production/ha were considered in the analysis, the emergy/culm value decreases in the same order as total emergy flow does. Also emergy indices change according to the labour transformity (see columns noted with "a" in Table 2), which strongly depends on location.

The EYR index reflects the ability to exploit and make local resources available by investing outside resources. In this way, this ability for the three countries decreases in this order: China, Brazil and Australia according to the EYR value of column "a" (1.70, 1.36 and 1.09, respectively). China uses 44% (sej/sej) of the inputs of natural sources, Brazil, 25% and Australia only 8%, in order to carry out culms production. According to Agostinho et al. [10] intensive conventional agricultural systems have EYR values lower than 2, which is indicative of a high dependence on purchased resources.

The EIR index evaluates if a process is competitive by analyzing the proper use of the invested emergy by the economy when compared with other alternatives for the use of the same resources. The three countries (with values of EIR of 1.44, 2.75 and 11.57 for China, Brazil and Australia, respectively) show they poorly make use of the invested emergy (*F*), reflecting a low market performance.

The ELR is an index of the pressure the system exerts on the environment. According to Brown and Ulgiati [14], a value less than 2 represents low impact, values between 2 and 10, moderate impact, and greater than 10, big impact. Excepting China (ELR value of 1.44), production in Brazil (2.75) causes moderate impact and in Australia (11.57) causes big impact on the environment. It is important to note that the equal value for both EIR and ELR results for the slight weight of *N* inputs compared to other resources.

Even though being the systems characterized by a clear dependence on primary environmental resources, only bamboo production located in China with a ESI value higher than 1 [23] would attain the level of "medium-term" sustainability.

The ternary diagram of Fig. 4a illustrates the points, which represent each system according to the % of *R*, *N* and *F* resources. The diagram enables to visualize, even independently of the previous discussion, some of the observations already done.

The negligible percentage of *N* as well as the variable relative quantities of the *R* and *F* resources is clearly illustrated in the

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Table 1
Emergy evaluation of the bamboo plantation and harvest.

No.	Item	Unit	Data/ (unit/ha year)	Emergy/unit/ (sej/unit)	Ref./ (emergy/unit)	Emergy/(sej/ha year) (10E + 13)	%/ (sej/sej)
	Renewable (R)						
1	Sun	J	5.53E + 13	1.00E + 00	[3]	5.53	–
2	Wind	J	2.45E + 09	2.52E + 03	[3]	0.62	–
3	Rain, geopotential energy	J	7.64E + 08	1.76E + 04	[3]	1.35	–
4	Rain, Chemical potential	J	6.42E + 10	3.06E + 04	[3]	196.30	19
5	Geothermic heat	J	1.00E + 10	5.78E + 04	[3]	57.79	6
6	*Implantation (R)					15.60	2
	Sub-total (sum of 4, 5 and 6). 1, 2 and 3 excluded to avoid double-counting					269.69	27
	Non-renewable (N)						
7	Soil erosion	J	4.52E + 06	1.24E + 05	[3]	0.06	<1
8	*Implantation (N)					0.03	<1
	Sub-total (sum of 7 and 8)					0.09	<1
	Purchased (F)						
	Fertilizer						
9	Nitrogen	g	6.00E + 04	7.07E + 09	[17]	42.44	4
10	Phosphorus	g	1.50E + 04	1.16E + 10	[17]	17.34	2
11	Potassium	g	6.00E + 04	4.97E + 09	[17]	29.84	3
	Machinery						
12	Steel	g	9.02E + 03	5.04E + 09	[18]	4.55	<1
13	Plastic	g	1.76E + 03	5.85E + 09	[19]	1.03	<1
							<1
14	Shale	g	4.00E + 05	1.68E + 09	[3]	67.20	7
15	Diesel oil	J	8.16E + 09	1.11E + 05	[3]	90.48	9
16	Labour (culture)	J	2.65E + 08	1.15E + 07	[Appendix B]	304.75	30
17	Labour (harvest)	J	1.40E + 08	1.15E + 07	[Appendix B]	161.00	16
18	*Implantation (F)					22.30	2
	Sub-total (sum of 9–18)					740.91	73
	Total emergy ($R + N + F$)					1010.69	100
	Yield (Y)						
	Culms produced	culm	1.60E + 03	6.32E + 12		1010.69	
		g	2.20E + 07	4.59E + 08		1010.69	
		J	4.18E + 11	2.42E + 04		1010.69	

The gross heating value was considered as 18.96 GJ/t for dried bamboo [20]. It was considered a moisture content of 15% at harvest. Details of calculation is available with the authors (biafgian@unip.br) or in ref. [21].
In order to unify global emergy budgets, present work adopted the value of 15.83E + 24 sej/year. In this way, transformity values on the older base were multiplied by 1.68. This procedure was carried out for transformities extracted from refs. [3,17,18]. Items 6, 8 and 18 are related to contributions employed during the first 7 years of system implantation. This period of 7 years was considered the time the system lasts to attain the steady state. During this time inputs like use of soil, labour, machinery and fuels were included. These values were depreciated along 68 years, by means 75 years of plantation lifetime minus the 7 years of implantation.

diagram since the three points are located on the R–F segment. As already discussed in terms of results from Table 2, only the point that represents production in China is positioned in the region of sustainability (Fig. 4a). Moreover, Australia represents the point more distant from the sustainability region.

When the influence of the indirect contribution of R is considered, emergy indices will change (see columns b of Table 2). The use of the indirect R perceptual is well-justified since at least within a macroeconomic approach, each human being profits a percentage of the country emergy which carries the same distribution of R, N and F resources as the whole country. The total emergy of Brazil has the contribution of 50% of renewable resources, Australia 49% and China 26% [15]. Thus, under this approach, labour flow can be considered as having the same proportion of R of the respective country. Recalculation of the indices on Table 2 leads to an improvement in all of them. EYR displays values almost reaching 2 for the three countries (1.99, 1.96 and 1.83 for Brazil, Australia and China, respectively). Also EIR shows values slight higher than 1 for the three countries (1.01, 1.04 and 1.02, in the same order). ELR attains values lower than 2 showing low impact, for all the countries (1.01, 1.04 and 1.02 for Brazil, Australia and China, respectively). The ranking of the countries suffers a modification when the indirect R resources are considered for human labour. In this way, Brazil attains the first place, followed by Australia and leaving in the

Table 2
Total emergy and emergy indices for the culms production calculated for the three countries: Brazil, Australia and China by using different labour transformities.

	EYR		EIR		ELR		ESI		Transformity (sej/J)	Total emergy (sej/ha ano) (10E + 13)
	a	b	a	b	a	b	a	b	a and b	a and b
Brazil	1.36	1.99	2.75	1.01	2.75	1.01	0.50	1.97	2.42E + 04	1010.7
Australia	1.09	1.96	11.57	1.04	11.57	1.04	0.09	1.89	8.12E + 04	3392.1
China	1.70	1.83	1.44	1.02	1.44	1.02	1.18	1.53	1.57E + 04	657.9

a corresponds to human labour without considering the indirect perceptual of R. b corresponds to human labour considering the indirect perceptual of R which according to each country will be: 50, 49 and 26% for Brazil, Australia and China, respectively.

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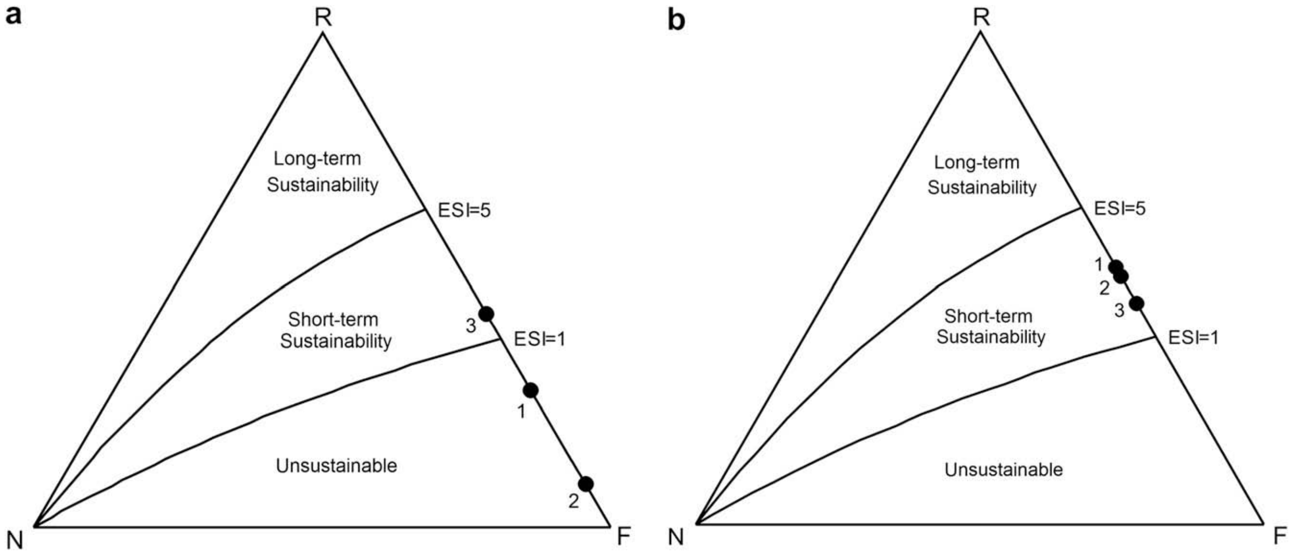

Fig. 4. Ternary diagram representing bamboo production systems: considering labour from Brazil (1), from Australia (2), and from China (3). (a) Without considering the embedded renewable portion of labour and (b) considering the embedded renewable portion of labour for each country.

last place China's production system. ESI values present all values higher than 1.

The displacement of the points towards the region marked in Fig. 4b as corresponding to $1 < \text{ESI} < 5$ (defined as "medium run" sustainability by ref. [23]) illustrates the changes already discussed from Table 2. Moreover, other aspects are evidenced in the triangular diagram: the extent of the displacement varies from point to point. The degree of variation depends on the % of *R* considered, but also on the transformity value of the labour for each country. In this way, systems affected by a higher % of *R* and higher transformity values will lead to higher displacements. This is the case of Australia, which combines high labour transformity and a value of % of *R* almost as highest as Brazil.

3.3. Exploring the relationship between sustainability and time

The idea of placing in the same graphic ESI and the global productivity (in this case the inverse of emergy/number of culms) seemed interesting since the area within the lines would represent a measure of the "goodness" of the systems under a sustainability point of view. In this way, it was defined the global productivity (GP) as being the inverse of the emergy/number of culms. The term "global" is consistent with the goal of emergy theory since the objective is to evaluate systems inserted in the whole biosphere. The GP has the units of number of culms/sej. A graphic showing the relationship between the ESI and GP is illustrated in Fig. 5 for the three countries. Each point represents the values of ESI and GP for the bamboo production system taking into account renewability embedded in labour for each country.

At a first glance, the graphic seems to provide a "preliminary ranking" based on differences among delimited areas. In this way, the biggest area would represent the best ranked system. But a careful analysis of the graphic enables to realize that a big area value *per se* does not satisfy the sufficient condition since a big area only would represent a measure of goodness if ESI and GP were restricted within acceptable values. The point corresponding to Australia location defines the biggest area. Even so, production in Brazil has a slightly better ESI value and an area comparable to that of China. However, it is clear that Brazil and China belong to opposite situations according to the relative ESI and GP values. The best production performance would be one which combines simultaneously acceptable values of ESI and global productivity. In this way, points located at the high right extreme would correspond to privileged positions. On the other hand, the worst situation lies on points located on the left-bottom side of the graphic. Furthermore, less direct situations result when the points are not located in the graphic extremes. For these cases, one of the parameters should be considered priority: high ESI value or high global productivity. Areas could be the same although one of the parameters is small or even unsatisfactory for the purposes to be achieved. These cases can account for low GP values when the concentration of a good portion of renewable resources could lead to ESI relatively high but without productivity; or high values of GP resulted from great economic investment and an unsatisfactory ESI. In this way, a big graphical area doesn't satisfy a sufficient condition to represent a good production performance.

Brazil presents the greater value of ESI, which would characterize a "medium run" sustainable production according to ref. [23]. On the other hand, it presents the worst GP value.

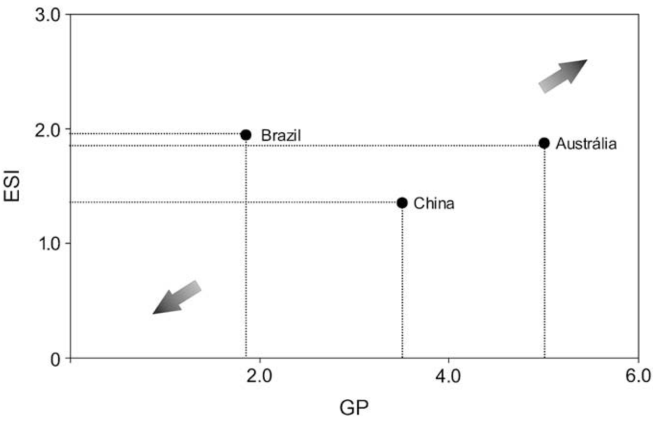

Fig. 5. Graphic ESI vs. GP (number of culms/sej) representing the three situations considered for human labour: Australia, Brazil and China. The embedded renewable parcel of labour according to each country was considered (50, 49 and 26% for Brazil, Australia and China, respectively). The ascendant arrow means good performance. The descendent arrow indicates the direction of bad performance.

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As a matter of fact, the concept “medium run” as well as “short” or “long run” that could be extracted from the ESI seems to be more appropriated for comparison among similar systems rather than to be used as an absolute criterion. In this way, it was adopted a period of 75 years for the lifetime of bamboo production, so an acceptable assumption of “medium run” might be 30 years. It is assumed that the system will maintain its situation of steady state by continuous consumption of inputs. This continuous supply of inputs (local or purchased) during a period of 30 years will certainly, affect macroeconomy. Changes in policy have their role also if long term is considered. In this way, it is important to recognize the determinant role of the larger system in which the system under study is inserted. This consideration leads to impose constraints due to the environment limitations of the surrounding. Thus, the points of the graphic represent a portrait of the present situation (with all the memory information) without the intention of undertaking a prospection of dynamic evolution between the systems and biosphere. Probably, Brazilian economy and policy will change during the next 30 years printing a different profile of the renewable parcel embedded in every purchased input that enters the system. Even maintaining the same production (same GP) with the same distribution of emergy flows, the work the biosphere has to do to maintain its supply will change. The possibility of operation within the sustainable values of ESI will depend on the broader scope of at least a national approach.

3.4. Exploring the relationship between sustainability and space

The total and relative quantities of resources (*R*, *N* and *F* inputs) that support a country economy tend to change with time. So do the areas needed to feed a given supply of resources to a system. Since territory is finite, the area, which could provide all the needed resources for an endeavor depends on surroundings profile. In this way, the area of domain of any economical system is larger than the actual occupied area.

The difference between the direct area demand (which represents the actual use of land) and the indirect required area (which represents the area that in fact supports the input of resources) is influenced by the inputs signature (their absolute and relative values) and the surroundings capacity for supplying the necessary resources.

The direct area demand depends on the amount of supporting emergy and if space or time is forced to decrease, required emergy to drive the process will naturally be forced to increase [23].

The indirect area represents the real area, which supplies the required services. It depends on the available environmental resources and is related with environmental load and the quantities of each type of input.

If it is assumed that all the environmental requirements are derived from renewable resources, the calculated “indirect area”, defined as the renewable support area ($SA_{(r)}$) will serve as a sustainability predictor of long term sustainability [16]. It represents the area required to provide the total emergy requirements to support economic development provided all the inputs were renewable.

In a complementary way, a second approach enables to predict short-term sustainability and it focuses on the fitness of development within an environmental system and local economy [13]. It is a measure indicator of the capacity of altering local cultural, economic and environmental patterns [16].

By considering that the $E_{\mathrm{mpd(r)}} = 4.18\mathrm{E}+14$ sej/ha and the Brazilian $\mathrm{ELR}_{(r)} = 1$ according to ref. [15], results were calculated from data of Table 1 and shown on Table 3.

Table 3
Comparative values for bamboo plantation in Brazil (with and without considering the indirect *R* percentage in human labour) and Brazil.

	Bamboo production	Bamboo production (with *R* parcel)	Brazil
Supporting emergy/(sej/ha ano)	10.11E + 15	10.11E + 15	8.36E + 14
R resources/(sej/ha ano)	2.70E + 15	5.03E + 15	4.18E + 14
N resources/(sej/ha ano)	9.00E + 11	9.00E + 11	3.31E + 14
F resources/(sej/ha ano)	7.41E + 15	5.08E + 15	0.87E + 14
% renewable	27	50	50
ELR	2.75	0.82	1
$SA_{(r)}$/(ha)	17.7	12.1	–
$SA_{(ELR)}$/(ha)	17.7	12.1	–

The percentage of *R* that supports bamboo production is lower than the one supporting the whole country. The only *R* resources correspond to chemical potential of rain, geothermic heat and some inputs related to implantation for bamboo production. When the renewability in labour is included, the % *R* increases from 27 to 50% sej/sej, comparable to the renewability that supports the whole country. The ELR of bamboo production is almost three times higher compared to Brazil’s ELR. By considering the indirect *R* included in labour, ELR remains smaller than the same indicator for Brazil. Empower for the endeavor is higher than Brazil empower. These differences led to $SA_{(ELR)}$ values greater than 1 ha for both considerations (17.7 and 12.1 for the case of neglecting and considering renewability in labour, respectively). So, the harvested bamboo exploited from 1 ha of plantation would correspond to 17.7 or 12.1 ha of real area in order to be equilibrated to the surroundings profile in terms of ELR. The necessary area that would be required if the economic activity were sustained by renewable *R* inputs is 17.7 or 12.1 ha (for the case of neglecting and considering the indirect *R* in labour, respectively) for each ha of bamboo plantation. Both areas present the same values due to the fact that in this particular case, $\mathrm{ELR}_{(r)} = 1$. The actual area of bamboo plantation is not able to provide its own resources.

4. Conclusions

Since the giant bamboo plantation system operates within a great interface with environment the high value of direct environmental inputs (rain and geothermic heat) is already expected, with 27% (sej/sej) of the total emergy. On the other hand, the intensive presence of human labour accounts for 30 and 16% at cultivation and harvest, respectively. Transformity value for bamboo culms production accounts for 2.42E + 04 sej/J. No works related to bamboo and emergy were found in literature in order to compare transformities values, but the value present the same order of magnitude of the transformity (3.2E + 04 sej/J) of a rainforest log [3].

The influence of transformity labour values leads to a crescent ESI ranking: China, Brazil and Australia. Only production located in China attains ESI values higher than one.

The option of considering the % *R* is more realistic although it is not a unified calculation procedure in literature. In this way, consideration of indirect renewability embedded in labour results in a ranking modification since the new indicators reflects the renewable resources distribution of each country. Consequently, bamboo production in Brazil is the best ranked, followed by Australia and with China in the last place. The three situations are located in the short-term sustainability region in the ternary diagram. An additional aspect is evidenced in the ternary diagram: the extent of points dislocation varies depending on the % R considered and also on the transformity value of the labour for each country. In this way, systems affected by higher % R and transformity values will lead to higher displacements. This is the case of Australia, which combines high transformity value and a value of % of R almost as high as Brazil.

A preliminary representation of "goodness" of the systems under a sustainability point of view is provided by the ESI vs. GP graphic, although some considerations have to be taken into account before any conclusion. In this case, excepting the unquestionable positions on the graphics the other ones have to be properly analyzed.

5. On the actual and potential usefulness of indirect area concept

Monetary units of an economy have an equivalent value in emergy contribution according to Odum [3], a fact that enables to establish a relationship more easily handled between emergy (something difficult to lead with and still unfamiliar) and money (the most familiar and directed way for humans to deal with wealth). In a complementary way with the indirect area concept, to establish a relationship between emergy and area enables not only to lead with a more easily handled equivalence but also to assign an adequate "preserved" area in order to "neutralize" the use of environmental resources. This "compensatory area" would act as a counterbalance to increase the ESI value within an acceptable interval. It is supposed to act analogously as the reinforcement effort the way Odum [3] referred to money feed back.

It is well known that developed countries tend to explore raw materials outside their borders while they aggregate value to those materials through technological procedures. In this case, purchased inputs (imported raw materials) use to come from under-developed or in development countries, having created great environmental disturbance in their native locals. Emergy accounting for the technological process performed in order to manufacture high technology products accounts also for the imported raw materials. If an indirect area will be calculated to establish the relationship with supporting emergy for the manufacturing process (maybe with the objective to adjust a "compensatory area"), it is important to be conscious that great disturbance was created elsewhere (probably far away the actual direct area location) as a consequence of exploitation. In this way, not always the establishment of the "compensatory area" (calculated through the indirect area approach) is the fairest procedure to perform sustainable investments or to achieve more equity in commercial transaction. The most disturbed local might not be directly beneficiated by that approach. But, in a global point of view the procedure could point a new or complementary direction towards sustainability if public policy began to act in accordance.

Appendix A

Results from Folio #4 [4] were selected because they represent a wide scope of crops and raw data were treated by the same analyst. This fact avoids effects of divergence due to different analysts' criteria.

Table 4 depicts in the second column the yearly energy of human labour invested per hectare (expressed in joules) for each crop [4]. As it was mentioned above in the text, this value is intrinsic of each system and represents the intensity of human presence as work done.

The third column shows original values of emergy flows related to human labour [4]. In this case, workers were considered as immigrants (uneducated workers) and transformity was calculated by considering work as a co product of the other human activities when only food and wages entered the system. As mentioned above in the text, the transformity value selected reflects a regional reality where workers are represented by immigrants. Original work [4] adopted a value of 4.45E + 06 sej/J for labour transformity.

On the other hand, the fourth column values of energy were expressed in emergy by multiplying them by the transformity of USA people. Transformity was calculated by considering that the whole support of the country (in emergy) is divided among population and metabolism.

Table 4
Comparative values of energy, emergy and % of human labour for different crops.

Crop	Energy of human labour (J/ha year)*	Emergy of immigrant labour (sej/ha ano)*	Emergy of national labour (sej/ha ano)**	% corresponding to migrant labour (sej/sej)*	% corresponding to migrant labour (sej/sej)* *disregarding services*	% corresponding to national labour (sej/sej)** *disregarding services*
Green beans	6.23E + 07	2.80E + 14	1.15E + 16	<1	3	8
Oats	4.79E + 06	2.00E + 13	8.81E + 14	<1	<1	15
Soybeans	7.34E + 06	3.00E + 13	1.35E + 15	<1	<1	28
Sugar Cane	1.37E + 07	6.00E + 13	2.52E + 15	<1	1	38
Peanuts	3.00E + 07	1.30E + 14	5.52E + 15	1	2	46
Pecans	4.53E + 07	2.00E + 14	8.34E + 15	2	4	62
Potatoes	1.37E + 08	6.10E + 14	2.52E + 16	4	6	71
Corn (sweet)	2.54E + 08	1.13E + 15	4.67E + 16	8	10	82
Tomatoes	8.56E + 08	3.81E + 15	1.58E + 17	10	14	87
Orange	2.71E + 08	1.20E + 15	5.00E + 16	13	15	88
Lettuce (romaine)	3.88E + 08	1.72E + 15	7.12E + 16	11	15	88
Watermelon	4.00E + 08	1.78E + 15	7.36E + 16	14	18	90
Cucumber	6.41E + 08	2.85E + 15	1.18E + 17	16	21	92

Data was extracted from ref. [4] and mathematically treated according to the present adopted criteria in order to enable comparison. *Original data from ref. [4]: migrant labour was considered. **Calculated by using the same criteria for transformity as in the present paper. In this way, the whole emergy of the country was considered to support human activities. Transformity of labour for USA workers (year of reference: 2000) was considered as 1.84E + 8 sej/J (calculated according to: total emergy supporting USA = 1.88E + 25 sej/year [23]; population = 2.85E + 08 people [23]; energy consumed by person/year = 3.59E + 08 J/person year, by considering 1.26E + 07 J as the metabolic energy requirements by day and 285 days of work). It was noted as "national labour". *Disregarding services*: in this case, services were unconsidered in order to enable comparison with results of the present paper. Services, according to ref. [4], includes aspects that were not accounted for in the present paper (services provided by more specialized labour and cost of land).

The next two columns represent the % of labour (expressed in sej/sej), but whereas the fifth one corresponds to original values as shown in ref. [4], the sixth neglects services. Services in ref. [4] mainly account for human services of more specialized professionals and land costs, inputs that were disregarded in the present work.

Last column derives from data of the fourth column since it represents the % of labour when those values were used. In order to maintain the same criterion adopted in the present work, services were discounted from total emergy to calculate percentage.

Appendix B

Table 5
Necessary data for calculation and way to calculate transformity of national labour.

Number	Item	Value	Units
1	Annual total emergy supporting Brazil per capita	4.13E + 16	sej/capita year
2	Human metabolic energy	1.26E + 07	J/day person
3	Energy involved during 285 days of work (excluding Sundays and holydays)	3.59E + 09	J/year person
4	Brazilian labour transformity (item 1/item 3)	1.15E + 07	sej/J

Raw data of item 1 was extracted from ref. [15].

Table 6
Comparative transformity of national labour for the three countries: Brazil, Australia and China calculated using the same procedure as in Table 5.

Country	Transfomity of national labour (sej/J)
Brazil	1.15E + 07
Australia	7.03E + 07
China	2.79E + 06

Appendix C

All raw data necessary to calculate emergy indices of Table 2 are listed as follows in Table 7. Data is extracted from Table 1 and only labour was recalculated according to the different labour transformities of each country. Columns symbolized with “b” referred to emergy values when the % R of each country (50, 49 and 26% for Brazil, Australia and China, respectively [15]) was adopted to recalculate labour emergy flow.

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Table 7
Total emergy values and discriminated R, N and F flows for bamboo production for the three countries labour transformities: Brazil, Australia and China.

	Total emergy/(sej/ha year) (10E + 13)		R/(sej/ha year) (10E + 13)		N/(sej/ha year) (10E + 13)		F/(sej/ha year) (10E + 13)	
	a	b	a	b	a	b	a	b
Brazil	1010.69	1010.69	269.69	502.57	0.09	0.09	740.91	508.04
Australia	3391.94	3391.94	269.69	1664.70	0.09	0.09	3122.16	1727.16
China	657.94	657.94	269.69	299.07	0.09	0.09	388.16	358.78

Recalculation calculated as in Table 5. a corresponds to human labour without considering the indirect perceptual of R. b corresponds to human labour considering the indirect perceptual of R which according to each country will be: 50, 49 and 26% for Brazil, Australia and China, respectively.

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