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# Energetic-environmental assessment of a scenario for Brazilian cellulosic ethanol

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ABSTRACT

The end of the age of cheap oil and global warming are causing worldwide concerns about energy security and climate change mitigation. Recognizing that the continuous growth paradigm will not change at short to medium time periods, alternative energy sources to fossil fuels are being sought, in which a promising source seems to be that obtained from vegetal biomass. Specifically in Brazil, there are Conventional Ethanol Plants (CEP) using sugarcane, but due to the energy versus food debate and an increasing demand for ethanol, cellulosic ethanol produced by Biorefineries seems to be a viable option. The question is whether the Biorefinery is more sustainable than CEP. This work aims to assess the energetic-environmental performance of a Biorefinery scenario in Brazil, comparing its results against CEP and another alternative small-scale system. For this, a multi-criteria approach was considered through the following methodologies: Embodied Energy Analysis, Ecological Rucksack, Emergy Accounting and Gas Emission Inventory. Results show that Biorefinery scenario has better rating than CEP for the most indicators when the functional unit is mass of ethanol produced, but when dealing with overall system performance, the Biorefinery performance worse. Neither the Biorefinery nor CEP was superior for all indicators, showing the existence of a trade-off. On the other hand, the small-scale system suggests being the best alternative if the aim is to get higher energetic-environmental performance.


## 1. Introduction

Petroleum, natural gas and coal comprise about 87% of primary energy consumption worldwide (World Oil Outlook, 2010). This high demand considerably reduces the natural stocks and has been projected to be on the decline due to scarcity during next decade; this phenomenon is called Peak Oil and characterized by high energetic and economic cost to make oil available (Campbell and Laherrére, 1998; Cleveland, 2005). Since the energetic issue is an urgent and real problem, and since that energy market affects globally the political-monetary balance, alternative energy sources to fossil fuels are considered extremely important for governments, scientists and entrepreneurs worldwide. Other resources are also crucial to society, for example fresh water, agricultural lands and food (Meadows et al., 2004; Hall and Day, 2009; MEA, 2005), but their importance has not yet garnered as much attention as fossil fuel and climate change.

Considering that world energy demand is predicted to increase by 40% (from a 2010's consumption of 230 million barrels of oil equivalent to 323 millions in 2030 World Oil Outlook, 2010), some biofuels are being considered part of the answer to move to a low carbon-emitting fuel for transportation. Nevertheless, there are several technological routes and raw material available for biofuel production and the characteristics of a specific route should never be generalized to any biofuel, because it depends on how and where it is produced. Brazil is recognized as a huge producer of first generation sugarcane ethanol, reaching 28 billion liters in 2008/2009 (UNICA, 2011), corresponding to 12% of all liquid fuel used for transportation in Brazil (Balanço Energético Nacional, 2011). To reach that high sugarcane production, 6.7 Mha of land using conventional agriculture were required (UNICA, 2011).

Large-scale ethanol production and its expansion are being criticized by some researchers based on arguments related to net energy output, biofuel versus food competition for land, water consumption in ethanol production, labor quality during harvest season, among others (Santa Barbara, 2007; Giampietro and Mayumi, 2009; among others). Trying to overcome these criticisms and to be well received by society, scientists are conducting research aimed at producing ethanol from lignocellulosic material, called as second generation ethanol. This production process maximizes waste reduction through the closed-industries concept,

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**Nomenclature**

| | |
|---|---|
| AP | Acidification Potential |
| CEP | Conventional Ethanol Plant |
| EROI | Energy Return on Investment |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| IFEES | Integrated Food, Energy and Environmental Services production |
| SUMMA | Sustainability Multi-Criteria, Multi-Scale Assessment |

i.e. material and energy previously considered as by-products by one process are fed back to other processes as raw materials. This approach resulted on the Zero Emission definition (Gravitis et al., 2008), the concept that will be applied to the new ethanol plants, Biorefineries.[1]

The concept of biomass refining has been a subject of discussion for more than 25 years motivated by potential for enhanced energy security, climate change mitigation, and rural economic development (Laser et al., 2009). Biomass energy and material recovery is maximized when a Biorefinery approach is considered, because many technological processes are jointly applied (Cherubini and Ulgiati, 2010). Different Biorefinery pathways, from feedstock to products, can be established according to the different types of feedstock, conversion technologies and products. Generally, the two technological routes are bio-chemical (enzymatic hydrolysis, and fermentation) and thermo-chemical (gasification). The choice about one route rather than the other depends on several aspects including political, economic, social, raw material availability, market for products, infra-structure, land and water availability, and so on. There is much time before a Biorefinery will be installed in Brazil and, in practical terms, Seabra et al. (2010) argues that for the Brazilian case there is a possibility to use sugarcane residues[2] to produce more ethanol in adjacent plants of sugarcane mills already installed.

An assessment of different aspects of a Biorefinery is mandatory for a better decision about which technological route should be chosen, verifying their strengths and weaknesses. In this sense, several papers are being published about technological and economic aspects of Biorefineries (Laser et al., 2009; Cherubini and Ulgiati, 2010; Luo et al., 2010; among others). On the other hand, the energetic-environmental issues are rarely discussed, and when they are considered, often only the Energy Return on Investment (EROI) index and the amount of $CO_2$ released to atmosphere are calculated. The technological and economic aspects are important, but to get a sustainable production, socio-politics and energetic-environmental issues are fundamental. Focusing on this last topic, the following doubt arises: Does the new second generation ethanol plant envisaged for Brazil have better energetic-environmental performance than the current first generation ethanol plant?

The Sustainability Multi-criteria Multi-scale Assessment (SUMMA) approach (Ulgiati et al., 2006) has been proposed as an alternative evaluation technique assessing the energetic-environmental performance of products and processes. This approach aims to use different methodologies with their own rules and meanings, avoiding the generation of one over-simplified final indicator. Moreover, the SUMMA allows decision makers to have access to a range of indicators showing different aspects of the system instead just one or two, supporting the choice for one or the other technological route for Biorefinery.

The objective of this work is to assess, through a multi-criteria approach, the energetic-environmental performance of a Biorefinery scenario in Brazil. Four main methodologies are used: Embodied Energy Analysis, Ecological Rucksack, Emergy Accounting and Gas Emission Inventory. Data for first generation large-scale ethanol and also for the Integrated Systems of Food, Energy and Environmental Services (IFEES) production calculated by Agostinho and Ortega (2012) are used for comparison.

## 2. Materials and methods

### 2.1. Biorefinery scenario

One of the main aspects for the future development of Biorefineries is the efficient production of transportation liquid biofuels. This is explained due to the increase of energy demand in the transportation sector, and the demand for renewable fuels, which can only be produced from biomass (Cherubini and Ulgiati, 2010). This is a crucial point, because currently only liquid fuel for transportation (ethanol) is considered in almost all energy discussions in Brazil, i.e. ethanol production is the mainstream and all other co-products do not receive the same importance (except for electricity production in some cases). The sustainable production of ethanol must be the target, in which a Biorefinery plant is suggested as a potential alternative.

Specifically for Brazilian case, Bonomi (2010) argues that the choice between different technological routes for second generation ethanol production must consider aspects related to eco-efficiency of hydrolytic process and aspects related to operational costs and flexibility of operational systems. Due to financial issues, infrastructure already installed for first generation ethanol production, and profitable production in existing ethanol plants, a radical change in ethanol production in Brazil from short to medium time periods is not expected. The same author suggests the following potential scenario for cellulosic ethanol production in Brazil: first generation ethanol production is maintained, but the surplus sugarcane bagasse and trash are now converted into ethanol by hydrolysis and fermentation of C6 sugars – the lignin is burned to generate steam and electricity. Still regarding the Brazilian case, Seabra et al. (2010) argues that for biochemical conversion, significant cost reductions may be achieved through process integration with the conventional mill, avoiding capital expenses and increasing the utilization of the existing installed capacity. For thermochemical conversion, process integration is more difficult, but different options arise when gasification systems are considered. In short, according to Bonomi (2010) and Seabra et al. (2010), the Brazilian scenario would entail hydrolyzing bagasse into cellulosic ethanol and steam and electricity produced by burning sugarcane trash; for this, an adjacent plant is more feasible than an abrupt change of the current first generation ethanol plants.

A plausible scenario for a Biorefinery in Brazil would be an adjacent plant to current ethanol plant that will produce cellulosic ethanol from a fraction of sugarcane bagasse (see Fig. 1). The sugarcane trash harvested will be totally burned to produce steam and electricity. The industrial processes of the adjacent plant would be: (i) pre-treatment of bagasse through steam explosion and sulfuric acid, splitting the biomass into cellulose, hemicellulose and lignin; (ii) enzymatic hydrolysis to convert cellulose and hemicellulose into fermentable sugars (glucose $C_6H_{12}O_6$ and xylose

[1] Biorefinery can be defined as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". This means that Biorefinery can be a concept, a facility, a process, a plant, or even a cluster of facilities (de Jong et al., 2009).

[2] One ton of cane stalks (or simply ton of cane) contains about 150 kg (dry) of sugars and 125 kg (dry) of fiber. Tops and leaves, called as "cane trash" or "sugarcane residues", represent an additional 140 kg (dry) of biomass per ton of stalks.

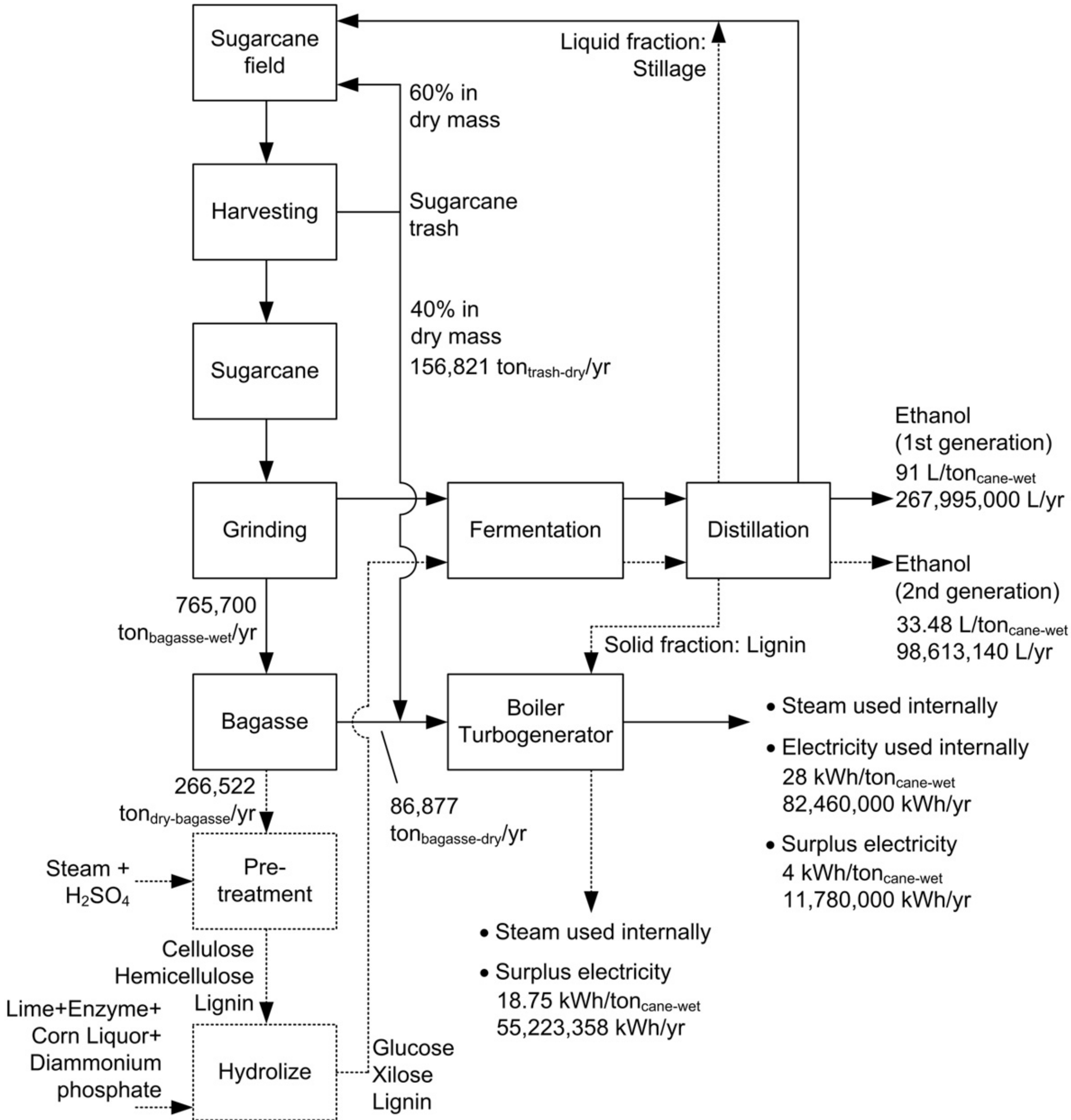


**Fig. 1.** Scheme of technological route for the biorefinery scenario considered in this work.

$C_5H_{10}O_5$); (iii) biological fermentation of $C_5$ and $C_6$ sugars; (iv) ethanol distillation; (v) liquid-solid (stillage-lignin) separation; (vi) stillage feed-back to sugarcane field as fertilizer – at long time periods it could be used for biogas conversion; (vii) lignin burnt to produce steam and electricity – at long time periods it could be used as raw material for Fischer-Tropsch fuels or Hydrogen.

### 2.2. Sustainability multi-criteria multi-scale assessment

Decision makers need signals to inform choices between different technological routes available for Biorefineries. These signals should be indicators showing different aspects of systems. Often, the analysts responsible for calculating and supplying indicators consider only one or two methodologies, disregarding other important aspects and drawing conclusions not expressed by the indicators calculated. For instance, to choose a technological route based only on its EROI index or on the amount of $CO_2$ released to the atmosphere is not sufficient to determine if a system is sustainable. We believe that determining the appropriate technological route should be based on several indicators from different methodologies, in which economic, social and energetic-environmental aspects are considered.

Methodologies used to assess the economic performance (i.e. profitability, revenue, capital costs, operating cost, selling price, net present value, internal rate of return, and so on) are well developed and commonly applied (see for instance Laser et al. (2009), Seabra et al. (2010), Luo et al. (2010) and Clausen et al. (2010). On the other hand, social aspects are more difficult to be evaluated because they require qualitative (work conditions, quality of life, etc) and quantitative (employment amount, income, etc) information. Unfortunately we were not able to find studies about social issues regarding Biorefineries, but we believe that only small changes will occur compared to current CEP; the only significant change on the reduction of labor during sugarcane harvest, because it will be totally mechanized. Studies about social issues on Brazilian CEP can be found at Mendonça and Rosset (2009), Jonasse (2011), Comar and Ferraz (2008), Martinelli et al. (2011), Hall et al. (2009), Schaffel and La Rovere (2010), among others. Focusing on the energetic-environmental performance, some efforts are being applied to assess the following aspects: greenhouse gas (GHG) emission, water consumption and fossil fuel consumption (Mu et al., 2010; Seabra and Macedo, 2011) GHG displacement, petroleum displacement, carbon dioxide emission, petroleum use, water use (Laser et al., 2009); impact categories from a Life Cycle Assessment (Luo et al., 2010); exergy efficiency (Ojeda et al., 2011). All of them are extremely important and must be considered in a simultaneous way. If the goal is providing a global picture of a process impact, then a selection of many indicators is needed in order to have a comprehensive evaluation across space and time scales. In this sense, we believe that a multi-criteria approach should be used, more specifically the Sustainability Multi-Criteria, Multi-Scale Assessment (SUMMA). The SUMMA approach was proposed by Ulgiati et al. (2006) and has been used in several Life Cycle Assessment studies. The authors choose to employ a selection of "upstream"[3] and "downstream" methods, which offer complementary points of view on the complex issue of environmental impact assessment. Each individual assessment method is applied according to its own set of rules. The calculated impact indicators are then interpreted within a framework in which the results of each method are compared.

Using SUMMA as reference, four methods were chosen to assess the energetic-environmental performance of the Biorefinery scenario considered here: (i) Embodied Energy Analysis, (ii) Ecological Rucksack, (iii) Emergy Accounting and (iv) Gas Emission Inventory. The same methods were applied to assess the Brazilian CEP and an alternative way to produce energy, food and environmental services in small scale in Brazil (IFEES[4]; Agostinho and Ortega, 2012), whose results are used for comparison against the values obtained for the Biorefinery scenario studied here. This comparison is made through two different approaches: (i) simple numerical comparisons considering each indicator separately (ii) and in a graphical way using a normalization approach. The normalization process considered here is based on the standard score approach, in which each individual value calculated is subtracted by the arithmetic mean of all values and divided by the standard deviation. The same approach was used by Ulgiati et al. (2011) assessing alternative fuels and biofuels production processes. Considering that the four methodologies used here supply many indicators and that to show all of them in a graphical way could create confusion, the analyst might select some indicators according to his/her experience or according to the specific target of the investigation. This selection should ensure the indicators are presented to decision-makers in the clearest manner. Once indicators are chosen, they can be normalized and diagrammed in such a way that their values can be compared to a reference value or year, or simply viewed together, in order to provide a global picture of the energetic-environmental system performance.

The four methodologies considered within SUMMA approach in this work are described in the next sub-items. For deeper information see Agostinho and Ortega (2012) that used the same methodologies and assumptions, as well as the original papers about methodologies quoted below.

#### 2.2.1. Embodied energy analysis

Energy Analysis is defined by International Federation of Institutes for Advanced Study (IFIAS) as the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service. According to Franzese et al. (2009), embodied energy analysis aims to quantify the availability and use of stocks of fossil fuels, sometimes also referred to as commercial energy, i.e. fossil fuel and fossil-equivalent energy. Embodied energy analysis focuses on fuels and electricity, fertilizers and other chemicals, machinery, and assets supplied to a process in terms of the oil equivalent energy required to produce them. Embodied energy analysis is concerned with the depletion of fossil energy, and therefore those process inputs of material and energy that do not require the use of fossil equivalent resources are not accounted for. Services provided for free by the environment such as soil building and groundwater recharge, are not accounted for within embodied energy analysis. Human labor and economic services are also not included in most evaluations.

Embodied energy analysis of a product or process is calculated by summing the raw energy input multiplied by its respective energy intensity factor. The more important final indicators of this methodology are (i) the total amount of embodied energy consumed by the system and (ii) its energy transformation efficiency reflected by EROI index (Energy Return on Investment). In this work, considering that both agricultural and industrial phases of ethanol production are accounted for, the first index is expressed as oil equivalent Joules per ha year ($J_{eq.}$/ha/yr), while the EROI index is obtained by dividing the output energy (calorific value) by the embodied input energy. The EROI index calculation results in a dimensionless value representing the system energy efficiency. Deeper understanding of Embodied Energy Analysis can be found mainly at Slesser (1974) and Herendeen (1998).

#### 2.2.2. Ecological rucksack

Material Flow Analysis (MFA) is defined by Eurostat (2001) as a method that assesses the efficiency of use of materials using information from material flow accounting. MFA helps to identify waste of natural resources and other materials in the economy that would otherwise go unnoticed in conventional economic monitoring systems. When dealing with the indirect material flows (upstream flows) and disregarding direct material flows (downstream flows), a subcategory of MFA is called Ecological Rucksack. The Ecological Rucksack method (Schmidt-Bleek, 1993) aims to evaluate the environmental disturbance associated with the withdrawal of raw material from its natural ecosystem. According to Eurostat (2001), the ecological rucksack can be defined as the total sum of all materials which are not physically included in the economic output under consideration, but which were necessary for production, use, recycling and disposal of indirect materials.

This methodology supplies important information related to load on environment caused generally far from system location. Appropriate rucksack factors are multiplied by each system input, accounting for the total amount of abiotic (i.e. the amount of inorganic matter that is excavated, transported and processed per unit of energy delivered) and biotic matter, water, and air that is indirectly required by system under analysis (Ulgiati et al., 2006). Due to lack of available information about rucksack factor for air category, this present work considered only abiotic, biotic and water categories.

[3] The "upstream" methods are concerned with the inputs, and account for the depletion of environmental resources, while the "downstream" methods are applied to the output, and look at the environmental consequences of the emissions (Ulgiati et al., 2006).

[4] IFEES is an acronym for Integrated Food, Energy and Environmental Services production. Basically, IFEES is a small-scale system (about 30 ha) that uses biomass as main energy sources instead petroleum, it maintains the traditional objectives of agriculture (i.e. producing food and raw material for other systems), labor is kept in rural areas and it produces environmental services through preserving native vegetation. See Agostinho and Ortega (2012) for detailed explanation.

### 2.2.3. Emergy accounting

Emergy is “the available energy of one kind previously used up directly and indirectly to make a service or product” (Odum, 1996). In accordance to the second law of thermodynamics, each transformation process degrades the available potential energy, but the “quality” of the remaining energy is increased. Emergy is considered a scientific measure of real wealth in terms of the energy previously required to make something; this is recognized as a donor side approach. Deeper understanding about emergy methodology rules and meanings can be found mainly at Odum (1996) and Brown and Ulgiati (2004).

For an emergy evaluation, the system under study must first be represented by a systemic diagram using the symbols proposed by Odum (1996). Subsequently, all raw values of the energy and mass flows of system are multiplied by their respective emergy intensity values (see Appendix A), resulting in flows with the same unit: solar emjoules (seJ). Finally, these flows are used to calculate emergy indices (Fig. 2) and draw conclusions about energetic-environmental aspects. A brief description of emergy indices used in this work is given below:

(a) Transformity is defined as “the solar emergy required to make 1 J of a service or a product” (Odum, 1996). It is obtained by the ratio of total emergy that was used in a process to the energy yielded by the process (Tr = U/Ep). Transformity is an expression of the quality of the output itself, for the higher the transformity, the more emergy is required to make the product flow.

(b) Renewability (%R = R/U) is the ratio of renewable emergy to total emergy use. It ranges from 0 to 100%, where higher values correspond to greater renewable emergy inputs from the environment. We considered here a modified renewability index (whose acronym is “m-%R”; m-%R = (R + Mr + Sr)/U), in which the partial renewabilities of each input were considered for its calculation, as proposed by Ortega et al. (2002).

(c) Emergy yield ratio (EYR = U/(M + S)) is the ratio of the total emergy driving a process to the emergy imported. It is a measure of the system’s ability to explore and make natural resources available through external economic investment, and reflects the potential contribution of the process to the main economy due to exploitation of local resources (Brown and Ulgiati, 2004).

(d) The emergy investment ratio (EIR = F/(R + N)) is the ratio of emergy fed back from outside a system to the indigenous emergy inputs (both renewable and non-renewable). It measures the intensity of invested emergy from the external economy (Brown and Ulgiati, 2004), assessing the relationship between the nonrenewable resources from the economy and natural resources.

(e) Environmental loading ratio (ELR = (N + F)/R) is the ratio of non-renewable and imported emergy use to renewable emergy use. It indicates the pressure on the environment produced by the system and can be considered as a measure of ecosystem stress. According to Brown and Ulgiati (2004), ELR values lower than 2 indicate low impact on the environment; values between 2 and 10 mean moderate impact; and values higher than 10 mean large impact. As well as for emergy renewability index, we considered in this study a modified ELR (whose acronym is “m-ELR”; m-ELR = (N + Mn + Sn)/(R + Mr + Sr)), in which the partial renewabilities were accounted for.

(f) Emergy Exchange Ratio (EER = U/($USD*emergy-to-dollar ratio)) is the ratio of solar emergy of the product sold by the mean solar emergy of the money received, in which the solar emergy of the money is the market value of product times the mean emergy-to-dollar ratio of the economy ($3.30 \times 10^{12}$ seJ/USD for Brazil in 2010; see Appendix A). The ratio is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the other (Brown and Ulgiati, 2004).

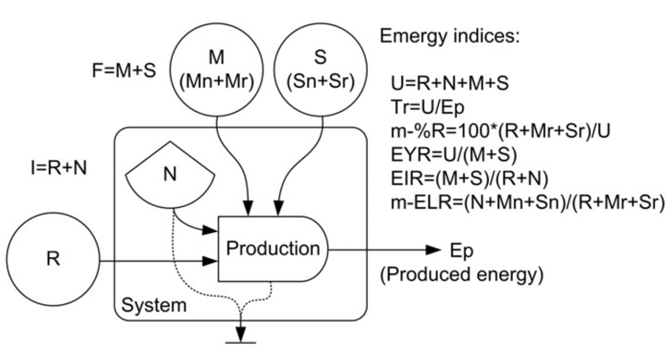


**Fig. 2.** Aggregated diagram and emergy indices used in this work. R: natural renewable resources; N: natural non-renewable resources; M: materials from economy; S: Services from economy; U: total emergy used by system; Tr: transformity; m-%R: modified renewability index; EYR: emergy yield ratio; EIR: emergy investment ratio; m-ELR: modified environmental loading ratio; “r” and “n” subscript means respectively renewable and non-renewable. Based on Brown and Ulgiati (2004).

### 2.2.4. Gas emission inventory

Gas emission inventory provides important information about global and local emissions. This work focuses on two categories of emission: (i) Indirect gas emissions and (ii) Direct gas emissions. Indirect gas emissions are those related to production of materials used up by the system; those emissions are generally located far from the system, but nevertheless cause global environmental load. To estimate the indirect emissions, all materials used up by the system were converted into their oil equivalents then multiplied by the emission factors provided by the United States Environmental Protection Agency (USEPA, 2008). Direct gas emissions are those caused by local material and fuel combustion. To estimate the direct gas emissions, only diesel fuel burned in engines was accounted for through the emission factors for combustion in tractors from USEPA (2008). Both direct and indirect gas emissions supply information about total CO, $NO_x$, PM10 (particles with 10 μm or less), $SO_2$, $CH_4$, $N_2O$ and $CO_2$ released into the atmosphere to produce an amount of product.

Additionally, the impact categories of Global Warming (GW) and Acidification Potential (AC) were estimated using the Jensen et al. (1997) approach. The following emission sources were not considered due to the lack of local emission factors data: (i) sugarcane bagasse and trash burned to produce steam and electricity, (ii) sugar fermentation process, (iii) emission from soil due to fertilizer use and (iv) land use change. Consequently, the final values of GW and AP obtained in this work may be underestimated, but they are useful for comparison against the values obtained by Agostinho and Ortega (2012), since both works do not account for the same emission sources. The same authors argue that there is no way to say what quantity of greenhouses gases released will increase the Earth’s temperature to a determined degree, but GWP is important to show the quantity of greenhouses gases released by production systems, and may be considered as one of the most important environmental parameters by decision makers. The same comment fits on AP, whose effects are seen as inefficient growth and, as a final consequence, dieback in softwood forests (e.g. spruce).

## 3. Results and discussion

### 3.1. Biorefinery in Brazil: a scenario approach

The main characteristics of the Biorefinery scenario previously shown on Fig. 1 are presented on Table 1. Raw data are average values from Macedo et al. (2008), Pereira and Ortega (2010) and Seabra et al. (2010). An ethanol plant producing only ethanol (instead ethanol and sugar as usual) was considered in this study; this approach does not influence the study because the ethanol and sugar production involves processes clearly distinguished, with specific equipment and energy use. Table 1 shows an increase on sugarcane and ethanol productivity compared to Conventional Ethanol Plant (CEP) assessed by Agostinho and Ortega (2012) (95 against 87 $ton_{wet}$/ha; 124.5 against 86.3 $L_{EtOH}/ton_{cane\text{-}wet}$), but the main aspect is that 40% of total sugarcane trash (i.e. tops and leaves of cane plant) is now harvested to be converted into steam and electricity, and the higher fraction of bagasse is converted into second generation ethanol.

Fig. 3 shows the systemic diagram of the Biorefinery scenario considered here, in which all input and output flows and internal feed-backs of energy and material are represented using the symbology proposed by Odum (1996). While Fig. 1 attempts to show technological and yield aspects, the systemic diagram aims to show, through a systemic view, all material and energy involved into the productive process, from natural or human-made sources. Basically, Fig. 1 is within Fig. 3, but system diagrams are an important tool for integrated assessment because they provide a pictorial description of the whole process, its driving forces, products recycling patterns, and interaction among components, which are all important aspects of an integrated assessment (see Brown (2004) for detailed meaning and importance of emergy diagrams). The Biorefinery depends on natural resources (symbolized by sun, wind and rain) for agricultural production, whose main objective is to produce sugarcane to be converted into ethanol, but, at the same time, the agricultural areas also produce environmental services; areas with natural vegetation are able to produce higher quantity of environmental services than agricultural ones, but all of them have their importance. Soil conservation is another important aspect because less soil loss means less organic matter and nutrient loss, reducing the load on the environment, demanding less fertilizer and consequently less economic investments. In addition to natural resources, the Biorefinery is dependent on human-made resources, mainly diesel, steel, lime, fertilizers, ammonia, enzyme and labor. Together, all energy and matter inputs allow the Biorefinery to produce ethanol and electricity. The negative externalities caused by the Biorefinery should not be ignored as they can negatively affect the surrounding region and also the biosphere; for instance, gas emission to atmosphere from processes, soil run-off containing nutrients and causing eutrophication of water bodies.

**Table 1**
Main characteristics of the biorefinery scenario assessed in this work.

| Characteristic | Unit | Biorefinery (mill + adjacent plant) |
|---|---|---|
| System location | – | São Paulo State |
| Time period for raw data | – | Scenario-2020 |
| Raw data source (mean values) | – | Macedo et al., 2008; Pereira and Ortega, 2010; Seabra et al., 2010 |
| System area[a] | ha | 38,750 |
| Sugarcane area | ha | 31,000 |
| Ethanol production capacity | L/yr | 267,995,000 (mill) + 98,613,140 (adjacent plant) |
| | $L/ton_{cane\text{-}wet}$ | 91 (mill) + 33.5 (adjacent plant) |
| Sugarcane productivity | $ton_{wet}$/ha | 95 |
| Mechanical harvesting | % | 100 |
| Crushed sugarcane | $ton_{wet}$ /yr | 2,945,000 |
| Stillage production[b] | $L_{vinasse}/L_{ethanol}$ | 10 |
| Sugarcane bagasse | $kg/ton_{cane\text{-}wet}$ | 260 |
| | $ton_{wet}$/yr | 765,700 |
| Sugarcane residues harvested | $ton_{dry}$/yr (%) | 156,821 (40) |
| Sugarcane residues (mill's boiler) | $ton_{dry}$/yr | 156,821 |
| Bagasse (mill's boiler) | $ton_{dry}$/yr | 86,877 |
| Bagasse (adjacent plant) | $ton_{dry}$/yr | 266,522 |
| Agricultural management | – | Conventional |

[a] System area = sugarcane area + natural vegetation area.
[b] Stillage (Vinasse) is an ethanol production residue. It is a liquid residue with high concentration of organic matter and nutrients that demands high levels of oxygen to be dissolved. Large-scale vinasse is spread in the sugarcane fields as fertilizer under suitable levels of application (~140 $m^3$ $ha^{-1}$).

Still regarding Fig. 3, harvested sugarcane is transported to the ethanol plant and converted into ethanol through first-generation processing. Additionally, a fraction of sugarcane trash is harvested to be burned in boilers and generate steam and electricity supplying the internal demand and exported to the grid. Unlike CEP, the Biorefinery scenario burns a small fraction of sugarcane bagasse (to produce steam and electricity) and the biggest fraction is used as lignocellulosic material for second-generation ethanol production. The byproduct lignin solid is then burned in boilers and the liquid stillage is transported back to the sugarcane field to be used as fertilizer. Money, represented by dashed lines, circulates on the system (Fig. 3, right side), in which money is received by selling products and used to pay for all human-made resources; it should be noted that there is not money circulating into the natural resources because they are considered infinitely available and not valued by conventional economic theory. The systemic diagram is important to show that all processes can only be driven through the use of external energy and matter resources from nature and economy, in which a sustainable system cannot depend strongly on non-renewable resources (for instance diesel), if not, there is no sense to promote it; as pointed out by Giampietro and Mayumi (2009), in some cases it is better to use diesel directly then to convert it in another fuel.

All resources demanded by the Biorefinery scenario can be seen at Table 2. The main inputs (in quantity) are water, soil loss, lime, seedlings, diesel, services and sulfuric acid. Differences compared to the CEP (Agostinho and Ortega, 2012) are related to an increase in the use of water (1.8 times more), diesel (1.5 times more), lime (2.5 times more) and a demand for new inputs such as enzyme, sulfuric acid and diammonium phosphate. The Biorefinery achieves high productivity of ethanol and electricity production compared to CEP: 9500 $L_{EtOH}$/ha/yr vs. 6000 $L_{EtOH}$/ha/yr, and 64 GWh $yr^{-1}$ vs. 25 GWh $yr^{-1}$. The environmental services production, represented here by water infiltration and $CO_2$ absorption, have the same values obtained by CEP, because the total area occupied by natural vegetation was not changed from the previous study (7750 ha); only the internal technological route of ethanol plant was changed from first- to second-generation.

Concerning the outputs, Fig. 4 shows that the Biorefinery is able to supply high amounts of ethanol and electricity to market compared to CEP and the small-scale system (IFEES). Even recognizing that the Biorefinery scenario considered in this work did not reach its full potential (e.g. it could have even higher energy and matter efficiency and also produce several different by-products as such chemicals and feed), it was able to produce about 2.6 more electricity and 1.6 more ethanol than the CEP. These production indicators are important but, according to Agostinho and Ortega (2012), if the target is the sustainable development of a society,

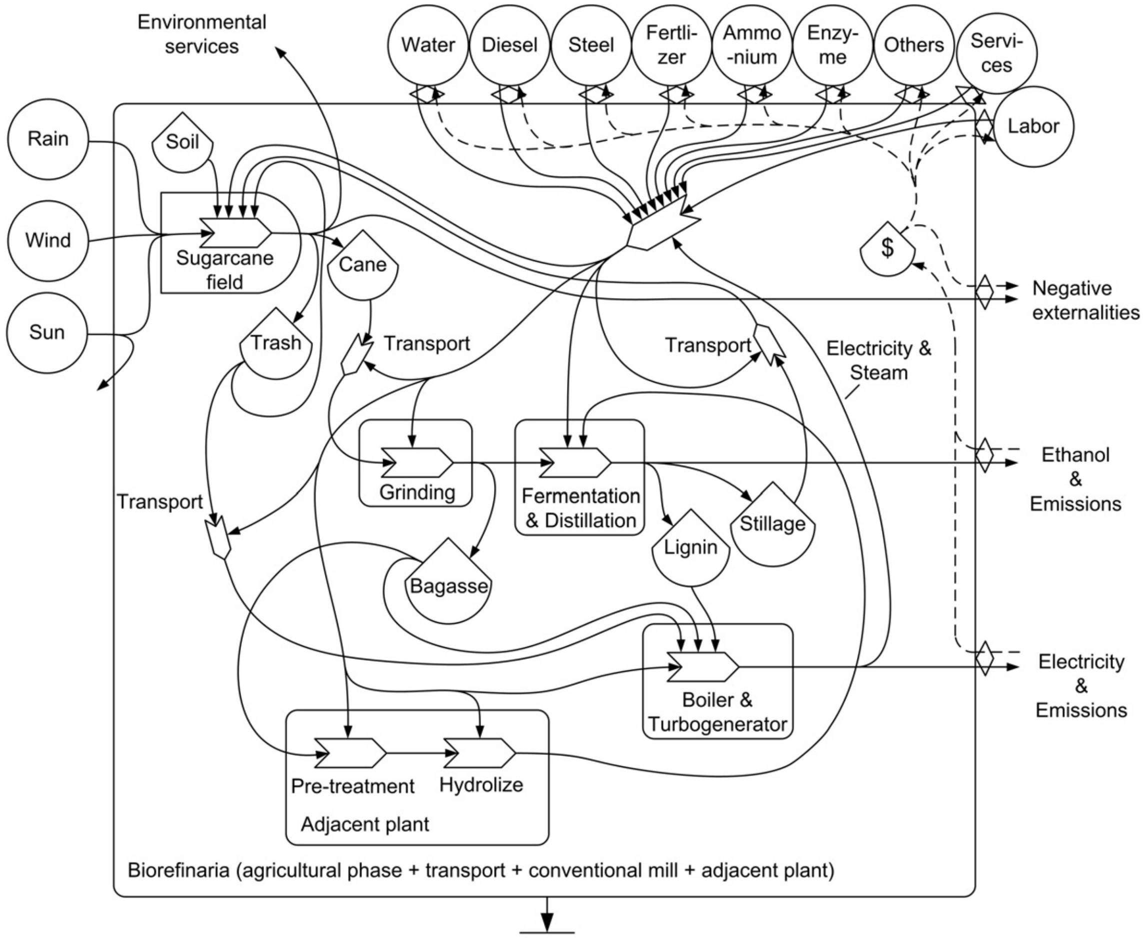


**Fig. 3.** Systemic diagram of the biorefinery assessed in this work.

then systems that are able to produce energy, food and environmental services (IFEES) should be also promoted. For instance, Fig. 4 shows that IFEES produces high amount of food, compost (organic matter used as fertilizer), timber wood and environmental services, but it makes available low amount of energy (ethanol and electricity); on the other hand, the Biorefinery and CEP are essentially energy suppliers. Which system should be chosen? Some argue that the evaluation of all indicators in a disconnected way could create confusion, and that a unique indicator able to merge all indicators should be used. For this, it could be considered weighting factors, but this approach is not recommended due to high level of subjectivity. For instance, considering the current demand of ethanol, one could give more importance for ethanol rather than food production, resulting in a better rating for the Biorefinery and CEP rather than the IFEES. On the other hand, one could give more importance to food and environmental services production instead ethanol, resulting in better rating for IFEES. Due to this subjectivity, we believe that the best way is to show all indicators at the same time, making clear the pros and cons and finally revealing which system is better for the interests of society.

The amount of ethanol, electricity and other materials produced are important as indicators to help decision-makers but not enough to promote a system. What are the economic, social and energetic-environmental costs for this high productivity? All these aspects must be considered simultaneously before to choose the better option.

### 3.2. Energetic-environmental assessment

#### 3.2.1. Performance for overall system: hectare year as functional unit

Table 3 shows the overall systems rating obtained from the SUMMA approach. Confirming our expectations, the Biorefinery scenario is able to produce annually a high amount of gross energy ($2.31 \times 10^{11}$ J/ha/yr), a value about 60% higher than Conventional Ethanol Plant (CEP) and 112% higher than small-scale system (IFEES). This could be considered as an excellent indicator for energy efficiency, but it is recognized that high net (and renewable) energy rather than high gross energy is the target.

*3.2.1.1. Embodied energy indices.* Energy efficiency is usually expressed by an output/input energy relationship, the Energy Return on Investment (EROI) index. It measures the system's capacity to transform one kind of energy into another, in which high values mean high efficiency. Table 3 shows that the overall energy efficiency (EROI) for the Biorefinery is 4.3, a similar value obtained by the CEP (4.6); this indicates that 4.3 units of one kind of energy become available for each unit used up by the Biorefinery. IFEES has an EROI of 13.2, showing net energy efficiency about 3 times higher than the Biorefinery and CEP; it must be highlighted that this efficiency reflects all energy output, including ethanol, food, forestry products and compost. Additionally, the IFEES

**Table 2**
Inputs and outputs of the biorefinery scenario assessed in this work[a].

| Item | Unit | Value |
|---|---|---|
| *Input* | | |
| #1 – Sun | $kWh/m^2/day$ | 5.00 |
| #2 – Rain | $m^3/m^2/yr$ | 1.40 |
| #3 – Wind | m/s | 4.70 |
| #4 – Water | kg/ha/yr | 174,080.00 |
| #5 – Soil loss | kg soil/ha/yr | 13,328.00 |
| #6 – Concrete | kg/ha/yr | 1.14 |
| #7 – Steel | kg/ha/yr | 11.31 |
| #8 – Copper (heat transfer) | kg/ha/yr | 0.56 |
| #9 – Rubber (tractor tire) | kg/ha/yr | 2.51 |
| #10 – Lime | kg/ha/yr | 1600.00 |
| #11 – Nitrogen | kg/ha/yr | 63.70 |
| #12 – Phosphorus | kg/ha/yr | 43.20 |
| #13 – Potassium | kg/ha/yr | 110.00 |
| #14 – Diesel | L/ha/yr | 350.00 |
| #15 – Seedlings | kg/ha/yr | 2800.00 |
| #16 – Herbicide | kg/ha/yr | 1.76 |
| #17 – Insecticide | kg/ha/yr | 0.13 |
| #18 – Enzyme (adjacent plant) | kg/ha/yr | 86.00 |
| #19 – Lime (adjacent plant) | kg/ha/yr | 336.00 |
| #20 – Water (adjacent plant) | kg/ha/yr | 26,200 |
| #21 – Sulfuric acid (adjacent plant) | kg/ha/yr | 461.00 |
| #22 – Diammonium phosphate (adjacent plant) | kg/ha/yr | 21.60 |
| #23 – Corn steep liquor (adjacent plant) | kg/ha/yr | 172.87 |
| #24 – Labor | h/ha/yr | 70.20 |
| #25 – Services | USD/ha/yr | 585.00 |
| *Output* | | |
| #26 – Ethanol | L/ha/yr | 9461 |
| #27 – Electricity | kWh/yr | 64,053,750 |
| Environmental services: | | |
| #28 – Water infiltration | $L_{water}/ha/yr$ | 840,000 |
| #29 – Potential carbon dioxide absorbed | $kgCO_2/ha/yr$ | 6776 |

[a] See Appendix B detailed calculation.

demands annually about 3.8 times less energy per hectare than CEP, and about 6.5 times less than the Biorefinery.

*3.2.1.2. Emergy indices.* Focusing on the overall emergy efficiency (higher transformities represent lower system efficiency), Table 3 shows the Biorefinery with better rating compared to other two

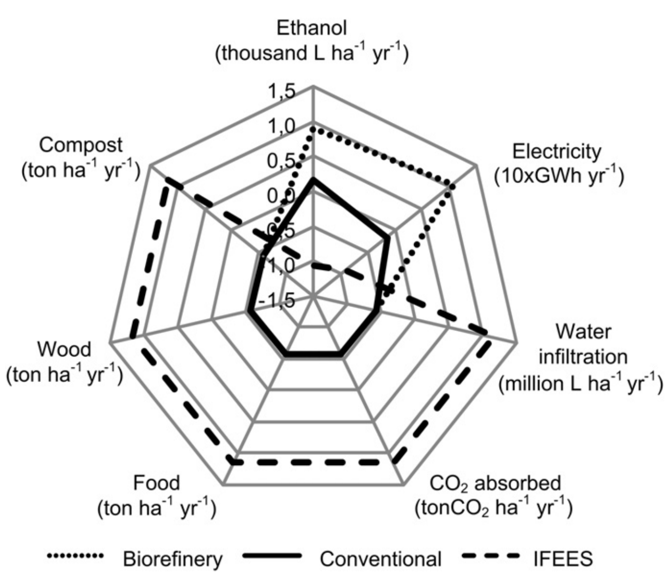


**Fig. 4.** Radar diagram comparing total energy and matter produced by three different systems. Biorefinery data from Table 2; data for conventional ethanol production and IFEES (integrated food, energy and environmental services production) systems from Agostinho and Ortega (2012).

systems – Biorefinery 58,000 seJ/J, IFEES 61,000 seJ/J and CEP with 71,000 seJ/J. It means that the Biorefinery demands about 5% less emergy to make available the same amount of gross energy output compared to IFEES and 22% compared to CEP. For comparison, the Transformity for gasoline and diesel is about 184,000 seJ/J (Brown et al., 2011), showing that all three systems assessed have higher emergy efficiency than gasoline and/or diesel. Transformity values are quite different from that obtained by EROI index, because EROI showed a better performance for IFEES. This happens because Transformity is an input/output ratio that includes all hidden costs (natural resources and labor through a large-scale view) not considered in an embodied energy analysis; this explains why emergy efficiency index differs from EROI.

Renewability index shows a lower renewability index for the Biorefinery (m-%R = 19%) compared to CEP (24%) and IFEES (54%). This low renewability was not a surprise because the Biorefinery scenario considered here is not representative of a definitive Biorefinery "*per se*", i.e. a small-scale industrial production aiming to produce several by-products from renewable biomass energy source. The Biorefinery considered here aims exclusively to increase ethanol and electricity production using sugarcane trash as biomass source. High productivity was reached, but an increase in material and energy demand was also increased. This characteristic is expressed by the low renewability, indicating an unsustainable scenario for the Biorefinery assessed here. For comparison, Pereira and Ortega (2010) obtained 31% renewability for a Brazilian sugarcane ethanol while Felix and Tilley (2009) obtained 21% for switchgrass cellulosic ethanol in USA. Brazilian's agrochemical agriculture has values ranging from 20 to 42% while ecological management values range from 56 to 73% (Agostinho et al., 2010; Cavalett and Ortega, 2010, 2009). Since non-renewable resources (derived from petroleum and mineral ores) are the driving forces of current large-scale ethanol production, their depletion over the next decades will be a great challenge for those production systems.

EYR shows better values for IFEES, because about 44% (EYR of 2.27) of its total emergy comes from external economic resources, while for the CEP and Biorefinery systems this percentage is about 66% and 72%, respectively. This shows that the dependency on economic resources (non-renewable resources) supporting the CEP and Biorefinery systems is high. In addition to the dependence of external economic resources, EYR also shows the potential contribution to the economy due to the exploitation of local resources; for the Biorefinery and CEP, this means that about 1.39 and 1.52 times more emergy become available to society by each emergy invested from economy, respectively, while for the IFEES this number is about 2.27. We must be aware that these EYR values can only be considered a positive aspect if the modified renewability index (m-%R) reaches values closer to those obtained by ecological agricultural management (i.e. at least higher than 50%). Thus, a value of 2.27 found for IFEES can be considered as "good" value, because it has a m-%R of 54% making it able to supply renewable energy to the economy; on the other hand, a m-%R of 19% and 24% obtained respectively by the Biorefinery and CEP show that the majority of emergy supplied to the economy comes from non-renewable resources. For comparison, EYR values ranging from 1.34 to 2.17 are typical for agrochemical Brazilian's agriculture, while ecological management has values from 2.24 to 3.69 (Agostinho et al., 2010; Cavalett and Ortega, 2010, 2009). Pereira and Ortega (2010) obtained an EYR of 1.57 for Brazilian sugarcane ethanol while Felix and Tilley (2009) obtained an EYR of 1.29 for switchgrass cellulosic ethanol in USA. An increase of indigenous renewable inputs rather than economic ones is extremely important because high use of renewable resources will be advantageous in a future scenario of oil scarcity.

**Table 3**
Embodied energy, emergy accounting and gas emission indices[a].

| Methodologies and their indices | Unit | Biorefinery (this work) | Conventional ethanol plant (CEP) [b] | IFEES[b] |
|---|---|---|---|---|
| Total energy output | J/ha.yr | 2.31E+11 | 1.45E+11 | 1.09E+11 |
| Embodied energy | | | | |
| EROI – Energy return on investment | – | 4.33 | 4.61 | 13.22 |
| Gross energy requirement | $MJ_{eq.oil}$/ha.yr | 5.33E+04 | 3.15E+04 | 8.23E+03 |
| Emergy accounting | | | | |
| Tr – Transformity | seJ/J | 58,300 | 71,500 | 61,300 |
| m-%R – Renewability[c] | % | 19 | 24 | 54 |
| m-%R – Renewability[c, d] | – | 19 | 24 | 52 |
| EYR – Emergy yield ratio | – | 1.39 | 1.52 | 1.70 |
| EYR – Emergy yield ratio[d] | – | 1.39 | 1.52 | 2.27 |
| EIR – Emergy investment ratio | – | 2.59 | 1.92 | 1.42 |
| EIR – Emergy investment ratio[d] | – | 2.59 | 1.92 | 0.79 |
| m-ELR – environmental loading ratio[c] | – | 4.29 | 3.10 | 0.85 |
| EER – Emergy exchange ratio | – | 0.93 | 1.14 | 0.94 |
| U – Total emergy | seJ/ha.yr | 1.34E+16 | 1.03E+16 | 6.67E+15 |
| Gas emission | | | | |
| Global warming potential | kg $CO_{2\text{-eq.}}$/ha/yr | 15,745.78 | 14,075.59 | 1644.40 |
| Acidification potential | kg $SO_{2\text{-eq.}}$/ha/yr | 65.89 | 59.42 | 2.95 |

[a] Observation: These indices correspond to the systems as a whole, not for one output alone.
[b] Agostinho and Ortega (2012) updated; Conventional sugarcane ethanol production in large-scale; IFEES is an acronym for the Integrated Food, Energy and Environmental Services production in small-scale.
[c] Considering partial renewability of each system's input.
[d] Without accounting for internal labor (only the IFEES has internal labor).

Focusing on EIR, IFEES has better value (1.42) compared to CEP and Biorefinery systems (1.92 and 2.59 respectively). This indicates that for each unit of energy from nature used up by IFEES, 1.42 units of energy are necessary from the economy. Inversely, if CEP is chosen as a supplier of ethanol and electricity, then it will supply 0.52 emergy units per each emergy unit invested from economy; for the Biorefinery this ratio is 0.39. Thus we can say that CEP has better rating for EIR than the Biorefinery, but only because its m-%R of 24%, higher than the 19% obtained by the Biorefinery. For comparison, Brazil's agrochemical agriculture has values ranging from 0.85 to 2.95, while for an ecological management, EIR ranges from 0.37 to 0.80 (Agostinho et al., 2010; Cavalett and Ortega, 2010, 2009). Regarding biofuel production, Felix and Tilley (2009) obtained an EIR of 3.42 for switchgrass cellulosic ethanol and Ulgiati (2001) obtained an EIR of 12.06 for corn ethanol in USA. The use of ecological management on agriculture and a reduction of the dependence on economic resources are necessary to increase the system's ability to use local renewable resources with low external investment.

According to a previous definition by Brown and Ulgiati (2004), ELR results in Table 3 show a low load (stress) on environment caused by IFEES (0.85) due to transformation activity, while CEP and Biorefinery systems cause moderate (3.10) and high (4.29) load, respectively. It must be noted that this load is a reflection of the systems dependence on non-renewable resources and does not represent the direct environmental impact downstream; as previously explained, Emergy Methodology is a "donor side" approach. For a simple comparison, m-ELR values ranging from 1.40 to 4.18 are typical for agrochemical-dependent Brazilian agriculture, while ecological management has values from 0.37 to 0.84 (Agostinho et al., 2010; Cavalett and Ortega, 2010, 2009). Regarding biofuel production, Felix and Tilley (2009) obtained an ELR of 3.87 for switchgrass cellulosic ethanol, Ulgiati (2001) obtained an ELR of 17.65 for corn ethanol in USA, and Pereira and Ortega (2010) obtained a m-ELR of 2.23 for Brazilian sugarcane ethanol.

The average EER value of 0.93 obtained by the Biorefinery and IFEES indicate that they are receiving more emergy when selling products than the total emergy used up in the production. It means that there is an emergy advantage for producers. On the other hand, CEP with an EER of about 1.14 indicates that it is delivering more emergy than receiving back in the trade operation, i.e. it has an emergy disadvantage. According to Odum (1996) (see also Cuadra and Rydberg (2006)), EER value could be used as a parameter to assess the market price of any good or service. Considering this approach, the market price of products sold by CEP should be increased, while the market price of products sold by the Biorefinery and IFEES should be reduced to reach emergy equilibrium.

*3.2.1.3. Global warming and acidification potential.* Table 3 shows a Global Warming Potential (GWP) of 15.5 $tonCO_{2\text{-eq.}}$/ha/yr for the Biorefinery, while CEP and IFEES have 14.1 and 1.6 $tonCO_{2\text{-eq.}}$/ha/yr, respectively. This indicates that the Biorefinery has higher potential to increase global warming. On the other hand, the IFEES has a potential about 9 times lower than the other two systems, indicating a much better rating. Still regarding Table 3, it is observed an AP of 66 kg $SO_{2\text{-eq.}}$/ha/yr for the Biorefinery while CEP and IFEES systems have 59 and 3 kg $SO_{2\text{-eq.}}$/ha/yr, respectively. The same tendency showed by GWP is seen here for AC, in which the Biorefinery has the worst rating followed by CEP. On the other hand, the IFEES has an AP about 20 times lower than both.

As explained before, this work considers the emissions related to diesel burned directly by agricultural engines (local emissions) and the indirect emissions related to the burn of heavy oil in industrial boilers to make the materials an energy consumed available for the Biorefinery (regional or global emissions). Thus, a better rating for the IFEES compared to other systems was expected, because it demands a lower amount of goods from economy, consuming about 9 times less diesel and 30 times less lime (in mass units per hectare per year) than the Biorefinery. On the other hand, contrary to the expected, the Biorefinery demands a higher amount of diesel (1.5 times higher) and lime (2.5 times higher) than CEP, resulting in a worse performance for GWP and AP. This rating is inverted comparing CEP and the Biorefinery, when the functional unit changes from ha year to mass of ethanol produced, justified by the higher ethanol productivity for Biorefinery than CEP (124.5 against 86.3 $L_{EtOH}/ton_{cane}$); this issue is discussed in detail on the next sub-item. Other interesting result is that about 60% of the GWP and AP for all three systems assessed are due to indirect emissions, usually not perceived by society, potentially hiding important sources of environmental burden.

*3.2.1.4. A joint view.* Selected indicators from Table 3 were displayed in a radar diagram (Fig. 5) in order to put data with different orders of magnitude together and provide visibility to the performance of the different systems. Those indicators plotted on Fig. 5 were chosen beyond all others because climate change mitigation and energy efficiency are the main driving forces for future Biorefineries. The large area on Fig. 5 indicates a worse performance, i.e. identifies the system that is characterized by the largest potential impact and lesser energy efficiency. Among the three systems, the Biorefinery has the worst performance in almost all indicators (only its Transformity is better compared to other two systems), suggesting that the Biorefinery scenario assessed here should not be promoted considering only the performance of the system as a whole. CEP has similar performance for EROI, GWP and AC compared to the Biorefinery, but its renewability and environmental loading ratio shows better values. Fig. 5 suggests that IFEES is the best option, because only its emergy efficiency is lower than the Biorefinery.

*3.2.2. Performance of ethanol produced: mass as functional unit*

In contrast to the previous section where all production was accounted for, now only the amount of ethanol produced is considered as functional unit (Table 4). Recognizing that all systems produce more than just ethanol, the allocation procedure in energy units adopted by Agostinho and Ortega (2012) was considered in this work to allow comparisons.

The embodied energy required to produce 1 kg of ethanol (1 kg = 1.25 L) by the Biorefinery (6.86 MJ) is similar to value obtained by CEP (6.44 MJ), but about 3 times greater than the value get by IFEES (2.24 MJ). This is reflected by the EROI index, in which for each Joule consumed by the Biorefinery, 4.33 J of ethanol are produced; for Conventional Ethanol Plant (CEP) and IFEES systems, this relationship is 1:4.61 and 1:13.2 respectively. These numbers indicate that ethanol produced by the Biorefinery scenario considered in this work has the lowest net energy efficiency compared to other two systems. For comparison, EROI values for Brazilian CEP found in literature are 3.7 (Oliveira et al., 2005), 9.3 (Macedo et al., 2008), 9.0 (Smeets et al., 2008) and about 8.2 (Pereira and Ortega, 2010). Corn ethanol has an EROI about 1.14 (Oliveira et al., 2005; Ulgiati et al., 2011) while switchgrass ethanol in USA has an EROI of 2.62 (Felix and Tilley, 2009).

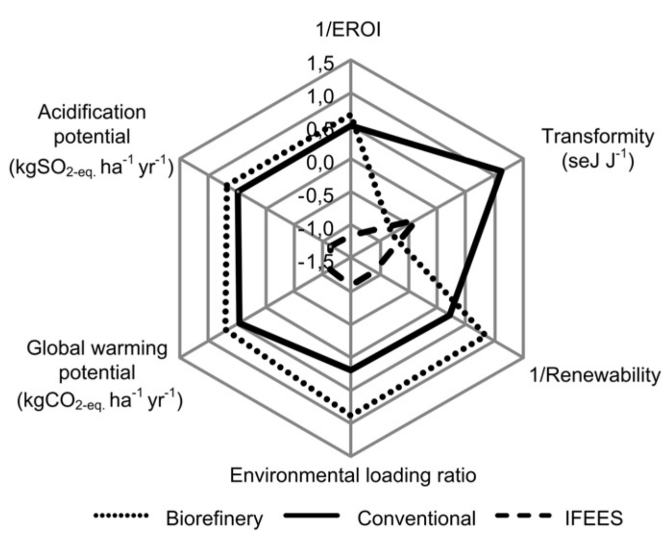


**Fig. 5.** Radar diagram with selected indicators for three assessed system. Biorefinery data from Table 3; data for conventional ethanol production and IFEES (integrated food, energy and environmental services production) systems from Agostinho and Ortega (2012).

Regarding the Ecological Rucksack method, Table 4 shows a huge advantage for ethanol produced by IFEES compared to Biorefinery scenario and CEP, because IFEES demands in average 3 times less abiotic material (non-organic material), 2 times less biotic material (organic material) and 10 times less water to produce 1 kg of ethanol. Comparing the Biorefinery against CEP, the latter demands about 40% more abiotic material, biotic material and water. Ulgiati et al. (2011) found the following values for corn ethanol in USA: 7.45 $kg_{abiotic}/kg_{EtOH}$, 0.35 $kg_{biotic}/kg_{EtOH}$ and 4811 $kg_{water}/kg_{EtOH}$. Regarding water consumption, Stone et al. (2010) obtained a demand of 2580 $kg_{water}/kg_{EtOH}$ from corn, 580 $kg_{water}/kg_{EtOH}$ from sugarcane and 1980 $kg_{water}/kg_{EtOH}$ from switchgrass.

The specific emergy shows that the Biorefinery is about 1.2 times more efficient than CEP and 19.4 times more efficient than IFEES if only ethanol is taken into account. To produce 1 kg of ethanol are necessary $1.78 \times 10^{12}$ seJ by the Biorefinery, while CEP and IFEES systems demand $2.16 \times 10^{12}$ seJ and $3.45 \times 10^{13}$ seJ respectively. Some Transformity values found in literature for fuels are: 110,000 seJ/J for switchgrass ethanol production (Felix and Tilley, 2009); 151,000 seJ/J for methanol from wood (Ulgiati, 2001); 189,000 seJ/J for ethanol from corn (Ulgiati et al., 2011); 187,000 seJ/J for gasoline, 178,000 seJ/J for natural gas and 181,000 seJ/J for Diesel (Brown et al., 2011). These values indicate that ethanol produced by the Biorefinery (59,900 seJ/J) is the best option if only emergy efficiency is considered as the decision parameter, followed by ethanol from CEP (72,700 seJ/J), switchgrass ethanol, methanol from wood and so forth. As observed by Agostinho and Ortega (2012), the value obtained by IFEES is misleading because it produces several products in addition to ethanol. Emergy evaluation does not allow an allocation procedure, thus the high heat value of ethanol produced by IFEES was divided by total emergy used by IFEES as a whole (including all products), resulting in low efficiency. On the other hand, the Biorefinery and CEP are specialized in ethanol production, and thus all emergy inputs are used up to produce basically ethanol; for these systems, the Transformity index shows the real emergy efficiency for ethanol production. A fair comparison should be made considering the small-scale system producing only ethanol, but the intentions of the IFEES are more varied, preventing it from being considered an exclusive ethanol production system.

In reference to gas emissions, ethanol produced by IFEES releases less gas compared to the Biorefinery and CEP (Table 4). The main differences are in $CH_4$, CO, and PM10 emissions, in which the Biorefinery and CEP release about 4,000, 133, and 44 times more than IFEES, respectively. Disregarding the hydrocarbons, in which the Biorefinery and CEP systems release about the same amount per ton of ethanol produced, in average the Biorefinery releases 50% less gas than CEP. This is reflected on impact categories, where CEP has about 43% more potential to cause Global Warming and Acidification than the Biorefinery per ton of ethanol produced. For comparison, Ulgiati et al. (2011) estimated a GWP of 2020 $kgCO_{2\text{-eq.}}$/ton of ethanol from corn, a similar value obtained here for sugarcane ethanol (2026 $kgCO_{2\text{-eq.}}$/ton for the Biorefinery and 2882 $kgCO_{2\text{-eq.}}$/ton for CEP). Considering solely gas emissions as the judgment parameter, the ethanol produced by IFEES should be strongly promoted instead the Biorefinery and CEP.

Fig. 6 shows the radar diagram considering some indices from Table 4. Again, due to the climate change and fossil fuel replacement concerns, the indices related to those issues were displayed, but we decide to add two indices related to water and abiotic material consumption. Even though these two indicators did not reach the same level of concern compared to climate change and fossil fuel issues, we believe that at short to medium time periods society will face problems with water and material availability. The large area on

**Table 4**
Environmental impact indices per unit of ethanol[a].

| Methodologies and their indices | Unit | Biorefinery (this work) | Conventional ethanol plant (CEP) [b] | IFEES[b] |
|---|---|---|---|---|
| Embodied energy | | | | |
| Energy intensity | $MJ/kg_{EtOH}$ | 6.86 | 6.44 | 2.24 |
| EROI | – | 4.33 | 4.61 | 13.22 |
| Ecological rucksack | | | | |
| Abiotic material consumption | $kg_{abiotic}/kg_{EtOH}$ | 3.76 | 4.91 | 1.50 |
| Biotic material consumption | $kg_{biotic}/kg_{EtOH}$ | 0.17 | 0.24 | 0.11 |
| Water consumption | $kg_{water}/kg_{EtOH}$ | 248.04 | 373.05 | 29.80 |
| Emergy accounting | | | | |
| Specific emergy (with L&S)[c] | $seJ/g_{EtOH}$ | 1.78E+09 | 2.16E+09 | 3.45E+10 |
| Specific emergy (without L&S) | $seJ/g_{EtOH}$ | 1.44E+09 | 1.63E+09 | 2.21E+10 |
| Transformity (with L&S) | $seJ/J_{EtOH}$ | 5.99E+04 | 7.27E+04 | 1.16E+06 |
| Transformity (without L&S) | $seJ/J_{EtOH}$ | 4.84E+04 | 5.50E+04 | 7.46E+05 |
| Gas emission | | | | |
| Hydrocarbons released[d] | g hydr./$ton_{EtOH}$ | 218.86 | 228.38 | 54.46 |
| Carbon monoxide released | g CO/$ton_{EtOH}$ | 84,557.77 | 134,060.86 | 817.06 |
| Nitrogen oxide released | g NOx/$ton_{EtOH}$ | 6944.93 | 9756.12 | 790.71 |
| Particulate matter released | g PM10/$ton_{EtOH}$ | 17,850.96 | 28,339.24 | 520.95 |
| Sulfur dioxide released | g $SO_2/ton_{EtOH}$ | 2368.90 | 3583.26 | 109.57 |
| Methane released | g $CH_4/ton_{EtOH}$ | 8877.30 | 14,120.38 | 2.77 |
| Nitrous oxide released | g $N_2O/ton_{EtOH}$ | 236.29 | 372.24 | 13.64 |
| Carbon dioxide released | g $CO_2/ton_{EtOH}$ | 1,271,580.15 | 1,684,051.03 | 442,856.01 |
| Global warming potential | kg $CO_{2\text{-eq.}}/ton_{EtOH}$ | 2026.47 | 2882.67 | 448.46 |
| Acidification potential | g $SO_{2\text{-eq.}}/ton_{EtOH}$ | 8480.44 | 12,168.65 | 805.39 |

[a] Allocation in energy units.
[b] Agostinho and Ortega (2012) updated; Conventional ethanol plant in large-scale; IFEES is an acronym for the Integrated Food, Energy and Environmental Services production in small-scale.
[c] L&S means Labor and Services.
[d] Assuming $CH_2$ as a basic hydrocarbon.

Fig. 6 indicates worse performance. Through an overall view, the Biorefinery has an advantage compared to CEP. On the other hand, while the Biorefinery uses less amount of abiotic material and water, and causing less global warming per kilogram of ethanol produced, it has lower energy efficiency (i.e. CEP is able to produce more ethanol through the use of the same amount of energy). The IFEES showed better values compared to other two systems: it is able to produce 1 kg of ethanol demanding less water, abiotic material, with lower GWP and higher energy efficiency, but it demands a high amount of emergy – the reader should remember that this is due to allocation issue as previously commented. Assuming that all indicators on Fig. 6 have the same weight during a decision, it is suggested that IFEES is the best option.

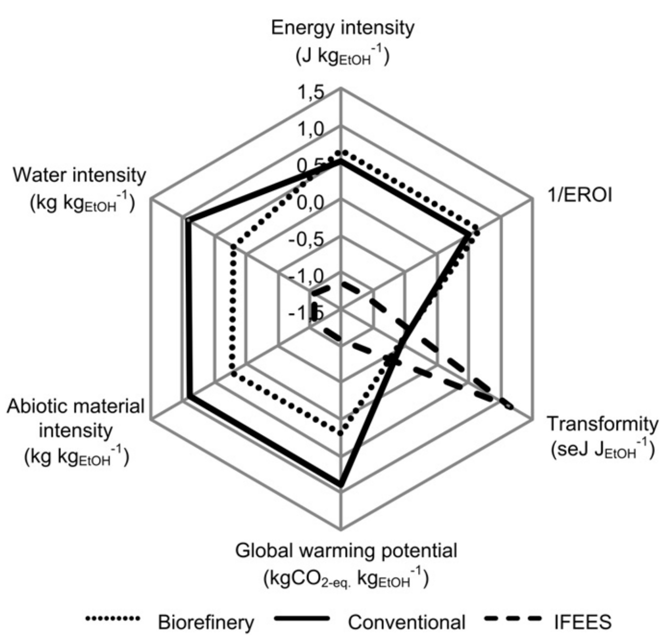


**Fig. 6.** Radar diagram with selected indicators representing the ethanol produced by three different systems. Biorefinery data from Table 4; data for conventional ethanol production and IFEES (integrated food, energy and environmental services production) systems from Agostinho and Ortega (2012).

### 3.3. General discussion

First, the reader must be aware that the Biorefinery considered in this work is not a commercial plant, rather it is a plausible scenario considering current tendencies in Brazil commented by some authors and assumed by us. Raw data and intensity factors used here were extracted from literature and, of course, the use of one reference rather than the other can produce different results. Even being considered important, a sensitivity analysis was not performed in this work because the scenario considered for the Biorefinery is very specific and basically its raw data came from only two papers, thus there is not a range of different raw data available that could change the final results. Moreover, the performance indices obtained for the Biorefinery assumed here were compared to other two systems assessed through the same methodologies and intensity factors; thus, the potential source of errors belong to all three systems. One important aspect that deserves refinement is the intensity factor for enzyme industrial production – the Biorefinery scenario assumes that enzyme comes from outside system boundaries. The intensity factor of chemicals was considered for enzyme (see Appendix A).

All indices obtained here for the Biorefinery scenario were compared to the other two different systems assessed previously by Agostinho and Ortega (2012): the Conventional Ethanol Plant (CEP) and the Integrated Food, Energy and Environmental Services (IFEES) production. Generally, the results can be divided into three parts: (i) focusing on total production; (ii) focusing on overall systems performance; (iii) focusing on ethanol production.

(i) Regarding total production, the Biorefinery is the best option if the gross energy production is the target. On the other hand, IFEES is able to produce large amounts of food, wood, compost and environmental services, but its ethanol productivity is about 25 lower than CEP and 40 times lower than the Biorefinery.

(ii) Recognizing that strong sustainability is mandatory for any economy and that the energetic-environmental aspects are important pillars of sustainability concept, assessing the systems performance as a whole is essential to the establishment of public policies for medium to long time periods. This approach aims to show that high productivity at any cost is no longer a winner strategy for sustainable economies. The indicators obtained show that IFEES has an EROI about 3 times higher than the Biorefinery and CEP, and it also demands 5 times less energy per ha year. Additionally, IFEES has a renewability of 55% against 20% for Biorefinery and 26% for CEP, its GWP and AP are about 9 and 21 times less than the Biorefinery and CEP. These numbers show that IFEES should be promoted to reach strong sustainability. The CEP has better rating than the Biorefinery in almost all indicators, except for gross energy output and Transformity. We believe that the energetic-environmental viability of cellulosic ethanol from sugarcane obtained from the Biorefinery scenario considered in this work is questionable because it had the lowest energy net yield and it relies upon non-renewable resources in its processes.

(iii) Focusing on ethanol production, the IFEES has higher EROI and it also demands about 3 times less energy to produce 1 kg of ethanol. Additionally, IFEES demands low material consumption and releases low amount of gases to atmosphere per mass of ethanol produced. On the other hand, the Transformity of IFEES shows emergy efficiency about 18 times lower than the Biorefinery and CEP. The Biorefinery has better values for water consumption, abiotic and biotic material demand, and it also releases lesser amount of gases to atmosphere compared to CEP, but its net energy efficiency is slightly lower than CEP.

Coming back to the research question (“Does the new second generation ethanol plant envisaged for Brazil has better energetic-environmental performance than the current first generation ethanol plant?”), we would say that still there is not a definitive answer. As demonstrated in this paper, there are many aspects regarding the environmental-energetic systems performance that must be considered. Someone can say that a specific aspect (represented by an index) is more important than the other, but this approach is always based on subjectivity. Recognizing that there is not a unique and “magic” indicator able to show the system performance fairly, and that may be a system will never be able to reach better rating for all indices, the radar diagrams aims to show which systems possess better overall rating. Considering the system as whole, Fig. 5 suggests that we would say NO to the research question, i.e. the Biorefinery does not have better energetic-environmental performance than CEP. On the other hand, considering only the ethanol output as functional unit (Fig. 6), we would say YES, ethanol produced by the Biorefinery has better energetic-environmental rating than CEP (this is a characteristic of economy of scale). Which system should be promoted? We believe that this decision depends strongly on the socio-economic development that politicians and society desires for the future of their Nation. If ethanol production is the target, then the Biorefinery should be promoted, but this will reduce the carrying capacity of the Biosphere (i.e. fewer stocks of material and energy will be available and the capacity to absorb the impacts will be reduced). If CEP is promoted, the ethanol production will remain on lower levels than supplied by the Biorefinery, but the load on environment from a global scale view will also be lower than caused by the Biorefinery. We believe that IFEES should be promoted instead of Biorefinery or CEP, or even a combination of them, because IFEES has better rating for the majority of indices assessed here, and as explained by Agostinho and Ortega (2012), it also aims for a paradigm change about socio-economic development. According to Santa Barbara (2007), a new way of looking at quality of life is demanded instead just more engineering. Not just more economic development, but a new sense of genuine global cooperation. Not just pursuing the chimera of nationalistic energy security, but a new paradigm based on social justice and ecological sustainability.

Results show the existence of a trade-off, in which each production system has better value for determined performance index rather than other. We believe that we will rarely see a “perfect” system with high performance in all aspects (i.e. economic, environmental, energetic and social). According to Galembeck (2010), careful attention is continually needed to avoid the environmental and social problems that will arise if short-term economic benefits receive priority over sustainable production objectives. A production system must be chosen, but this choice must consider the opinion of experts in different knowledge fields and also the general society, avoiding a decision based on desires of few people with political and economic influence.

## 4. Conclusions

Considering the methodologies and assumptions of this work, the follow conclusions can be drawn:

(a) Regarding total systems production – The Biorefinery is able to produce 1.57 times more ethanol than Conventional Ethanol Plants (CEP) and 40 times more than IFEES. Moreover, its electricity production is 2.58 times higher than CEP. On the other hand, IFEES also produces food, wood, compost and environmental services instead only ethanol.

(b) Regarding the energetic-environmental performance for a system as a whole – Disregarding Transformity index, the IFEES had better performance for all other indicators compared to the Biorefinery and CEP. Concerning large-scale systems, while the Biorefinery and CEP have similar net energy efficiency (EROI of 4.33 and 4.61), the Biorefinery has better emergy efficiency (58,300 versus 71,500 seJ/J). On the other hand, Global Warming and Acidification Potential of the Biorefinery are 11% higher than CEP, it also has higher load on environment (ELR of 4.29 versus 3.10) and lower renewability (19% against 24%).

(c) Regarding the energetic-environmental performance per unit of ethanol produced – Excluding Transformity, the IFEES has better rating for all other indicators. Concerning large-scale systems, the energy demand is similar for both ($\sim$6.6 MJ/kg$_{E\text{-}tOH}$), but all other indices showed a better rating for the Biorefinery: to produce 1 kg of ethanol, the Biorefinery requires 1.5 times less water and 1.3 times less abiotic material than CEP, its GWP and AC are about 43% lower and its emergy efficiency is 21% higher than CEP.

The final indicators show that Biorefinery scenario has better rating than CEP for some aspects but worse for others; a system with better performance for all indicators is rare. One system should be promoted instead another depending on objectives, for instance, the Biorefinery is the best option if an increase in ethanol production is the target, but a more sustainable ethanol production is obtained through IFEES followed by CEP and the Biorefinery.

The use of biomass as an energy source is not enough to ensure a prosperous future for later generation; the biomass must be properly produced and manufactured through low dependence on fossil fuel derivates. The ethanol produced by large-scale systems assessed here cannot be considered as a renewable energy source (neither as sustainable), they are energy consuming processes that provide a means for converting high amount of water, soil, fossil fuel, minerals, and other resources into ethanol liquid fuel. On the other hand, the IFEES is a better alternative when sustainability issues are considered as the mainstream within political discussions about economic growth. The results show that if the ethanol produced by the Biorefinery scenario assessed here is pushed by the political subsidy for biofuels, it will only accelerate the rate at which fossil fuel and other important materials (e.g. water, soil, iron ore converted into steel, and so on) are being depleted. Nevertheless, a “complete” Biorefinery (i.e. producing several different by-products as chemicals, fertilizers, feed, etc) seems to be the best option when dealing with strong sustainability, but its performance needs to be assessed by the same methodologies considered in this present work and others related to social-political and economic issues.

## Acknowledgements

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## Appendix A

**Table A1**
Intensity factors used in this work

| Item | Emergy accounting[a] | Unit | Ref. | Embodied energy[b] | Unit | Ref. | Ecological rucksack | | | Unit | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Abiotic | Biotic | Water | | |
| Sun | $1.00 \times 10^{00}$ | seJ/J | A | – | – | – | – | – | – | – | – |
| Rain | $3.10 \times 10^{04}$ | seJ/J | B | – | – | – | – | – | – | – | – |
| Wind | $2.45 \times 10^{03}$ | seJ/J | B | – | – | – | – | – | – | – | – |
| Water | $6.89 \times 10^{04}$ | seJ/J | C | – | – | – | – | – | – | – | – |
| Soil loss | $1.24 \times 10^{05}$ | seJ/J | D | – | – | – | 0.66 | 0.04 | 0.30 | kg/kg | Q |
| Concrete | $2.42 \times 10^{12}$ | seJ/kg | E | 160 | $kg_{eq}$/ton | M | 1.33 | 0.00 | 3.40 | kg/kg | R |
| Steel | $3.78 \times 10^{12}$ | seJ/kg | C | 1000 | $kg_{eq}$/ton | M | 9.32 | 0.00 | 81.90 | kg/kg | R |
| Cooper | $3.36 \times 10^{12}$ | seJ/kg | C | 1500 | $kg_{eq}$/ton | M | 170.07 | 0.00 | 236.39 | kg/kg | R |
| Rubber | $7.22 \times 10^{12}$ | seJ/kg | F | 2040 | $kg_{eq}$/ton | N | 5.70 | 0.00 | 146.00 | kg/kg | S |
| Lime | $1.68 \times 10^{12}$ | seJ/kg | C | 220 | $kg_{eq}$/ton | N | 1.44 | 0.00 | 5.60 | kg/kg | R |
| Nitrogen | $7.28 \times 10^{12}$ | seJ/kg | G | 1440 | $kg_{eq}$/ton | O | 1.10 | 0.00 | 0.00 | kg/kg | T |
| Phosphorus | $5.67 \times 10^{12}$ | seJ/kg | D | 260 | $kg_{eq}$/ton | O | 7.36 | 0.00 | 50.60 | kg/kg | R |
| Potassium | $1.85 \times 10^{12}$ | seJ/kg | A | 160 | $kg_{eq}$/ton | O | 11.32 | 0.00 | 10.60 | kg/kg | R |
| Diesel | $1.81 \times 10^{05}$ | seJ/J | H | 1580 | $kg_{eq}$/ton | O | 1.36 | 0.00 | 9.70 | kg/kg | R |
| Seedlings | $1.41 \times 10^{11}$ | seJ/kg | I | 38 | $kg_{eq}$/ton | H | 4.62 | 0.24 | 606.00 | kg/kg | U |
| Herbicide | $2.49 \times 10^{13}$ | seJ/kg | C | 5670 | $kg_{eq}$/ton | O | 1.10 | 0.00 | 0.00 | kg/kg | G |
| Insecticide | $2.49 \times 10^{13}$ | seJ/kg | C | 4740 | $kg_{eq}$/ton | O | 1.10 | 0.00 | 0.00 | kg/kg | V |
| Enzyme | $2.65 \times 10^{12}$ | seJ/kg | J | 320 | $kg_{eq}$/ton | N | n.d.a. | n.d.a. | n.d.a. | n.d.a. | n.d.a. |
| Diammonium phosphate (N) | $1.59 \times 10^{13}$ | seJ/kg | D | 1205 | $kg_{eq}$/ton | P | 7.07 | 0.00 | 50.80 | kg/kg | Q |
| Corn steep liquor (heat) | $5.54 \times 10^{08}$ | seJ/kg | K | 161 | $kg_{eq}$/ton | P | n.d.a. | n.d.a. | n.d.a. | n.d.a. | n.d.a. |
| Sulfuric acid | $1.53 \times 10^{11}$ | seJ/kg | D | 50 | $kg_{eq}$/ton | P | 0.25 | 0.00 | 4.10 | kg/kg | R |
| Labor | $7.21 \times 10^{12}$ | seJ/h | C | – | – | – | – | – | – | – | – |
| Brazil's emergy per money ratio | $3.30 \times 10^{12}$ | seJ/USD | L | – | – | – | – | – | – | – | – |

n.d.a. = no data available.
[A] Odum, 1996; [B] Odum et al., 2000; [C] Brown and Ulgiati, 2004; [D] Brandt-Williams, 2002; [E] Buranakarn, 1998; [F] Luchi and Ulgiati, 2000; [G] Cavalett and Ortega, 2009; [H] Brown et al., 2011; [I] Estimated in this work. See Note#15 on Appendix B; [J] Assumed as chemicals from Odum (1996); [K] Felix and Tilley, 2009; [L] Coelho et al., 2003; [M] Jarach, 1985; [N] Boustead and Hancock, 1979; O Ozkan et al., 2004; [P] Mu et al., 2010; [Q] Assuming a soil with 4% of organic matter, 30% of water and 66% of inorganic matter; [R] WICEE, 2003; [S] Assumed as synthetic rubber from WICEE (2003); [T] Cavalett and Ortega, 2010; [U] Assumed as seeds from Cavalett and Ortega (2010); [V] Assumed as herbicide from Cavalett and Ortega (2009).
[a] Emergy intensity values accounting for labor and services for human made processes. Emergy baseline of $15.83 \times 10^{24}$ seJ/yr from Brown and Ulgiati (2004).
[b] eq. = equivalent oil; 1 ton-eq. = 42 GJ (Jarach, 1985).

## Appendix B. Raw data calculation for Table 2

Note#1 (Sun) – Solar radiation = 5 kWh $m^{-2}$ $day^{-1}$ (www.cresesb.cepel.br); Albedo = 20% (Odum, 1996); Conversion = (kWh/$m^2$/yr) (1 – Albedo) (10,000 $m^2$ $ha^{-1}$) (3,600,000 J $kWh^{-1}$) (365 days $yr^{-1}$); Input flow = $5.26 \times 10^{13}$ J/ha/yr.

Note#2 (Rain) – Rainfall = 1.4 $m^3$ $yr^{-1}$ (www.sirgh.sp.gov.br); Gibbs free energy = 5000 J $kg^{-1}$ (Odum, 1996); Water density = 1000 kg $m^{-3}$; Conversion = ($m^3$/$m^2$/yr) (J/kg) (kg/$m^3$) (10,000 $m^2$ $ha^{-1}$); Input flow = $7.00 \times 10^{10}$ J/ha/yr.

Note#3 (Wind) – Air density = 1.3 kg $m^{-3}$; Average of annual velocity = 4.7 m $s^{-1}$ (www.cptec.inpe.br); Geotropic wind = 2.82 m $s^{-1}$ (assumed as 60% of annual velocity (Rodrigues et al., 2002); Drag coefficient = 0.001 (Rodrigues et al., 2002); Conversion = (kg/$m^3$) $(m/s)^3$ (0.001) (10,000 $m^2$ $ha^{-1}$) ($31.56 \times 10^{06}$ s/yr); Input flow = $9.20 \times 10^{09}$ J/ha/yr.

Note#4 (Water) – Water consumption of 18.4 $L_{water}/L_{ethanol}$ or 1.6 $m^3$ water/ton crushed sugarcane (Pereira and Ortega, 2010). It includes only industrial phase, because sugarcane irrigation in Sao Paulo State is used only in special cases due to excellent climate conditions. Ethanol produced = 366,608,140 L $yr^{-1}$ (see Note#25). Gibbs free energy = 5000 J/$kg_{water}$ (Odum, 1996); Conversion = ($L_{water}/L_{ethanol}$) ($L_{ethanol}$/yr) (1 $kg_{water}/L_{water}$) (J/$kg_{water}$) (1/38,750 ha); Input flow = 174,080 kg $ha^{-1}$ $yr^{-1}$ or $8.70 \times 10^{08}$ J/ha/yr.

Note#5 (Soil loss; organic matter) – Average value for soil loss of conventional sugarcane production = 11,900 $kg_{soil}$/ha yr (Pereira and Ortega, 2010); It was assumed an increase of 40% for soil loss for biorefinary, due to harvest of 40% in mass of cane trash. In the ground, this cane trash is important to reduce soil loss, but harvesting the trash to produce second generation ethanol and electricity, certainty it will increase soil loss. Organic matter content

(O.M.) = 4% (Odum, 1996); O.M. energy = 5400 kcal/kgO M. (Odum, 1996); Conversion = 1.4 ($kg_{soil}$/ha.yr) (0.04) (kcal/kgO M.) (4186 J $kcal^{-1}$) (31,000 $ha_{cane}$/38,750 $ha_{bioref}$); Input flow = 533 kg $ha^{-1}$ $yr^{-1}$ or $1.20 \times 10^{10}$ J/ha/yr.

Note#6 (Concrete) – Used in industrial building, office, laboratories, repair shops and yards = $4.43 \times 10^{04}$ kg/yr Macedo et al. (2008); Conversion = (kg/yr) * (1/38,750 ha); Input flow = 1.14 kg $ha^{-1}$ $yr^{-1}$.

Note#7 (Steel) – Total steel in equipments for a plant with 860,000 $L_{ethanol}$/day = 11,300 ton (Macedo et al., 2008); Reference for this study 1,000,500 $L_{ethanol}$/day = 13,146 ton; 30 years of lifetime; Conversion = (ton) (1000 kg/ton) (1/30 yr lifetime) (1/38,750 ha); Input flow = 11.31 kg $ha^{-1}$ $yr^{-1}$

Note#8 (Cooper) – Total cooper in equipments = 66 ton (estimated as 0.5% of total steel); Conversion = (ton) (1000 kg/ton) (1/30 yr lifetime) (1/38,750 ha); Input flow = $5.67 \times 10^{-02}$ kg $ha^{-1}$ $yr^{-1}$.

Note#9 (Rubber) – Total rubber used in tires of agricultural machines = 97,288 kg $yr^{-1}$ (Pereira and Ortega, 2010); Conversion = (kg/yr) * (1/38,750 ha); Input flow = 2.51 kg $ha^{-1}$ $yr^{-1}$.

Note#10 (Lime) – Total lime used considering a sugarcane five years cut = 10,000 kg/$ha_{cane}$ (Macedo et al., 2008); Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = $1.60 \times 10^{03}$ kg/ha/yr.

Note#11 (Nitrogen) – Total nitrogen used considering a sugarcane five years cut = 398 kg/$ha_{cane}$ (Macedo et al., 2008); Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = 63.68 kg $ha^{-1}$ $yr^{-1}$

Note#12 (Phosphorous) – Total phosphorous used considering a sugarcane five years cut = 270 kg/$ha_{cane}$ (Macedo et al., 2008); Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = 43.20 kg $ha^{-1}$ $yr^{-1}$

Note#13 (Potassium) – Total potassium used considering a sugarcane five years cut = 690 kg/$ha_{cane}$ (Macedo et al., 2008); Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = 110.4 kg $ha^{-1}$ $yr^{-1}$.

Note#14 (Diesel) – Total consumption = 350 L/$ha_{cane}$/yr (Seabra and Macedo, 2011); Conversion = (L/$ha_{cane}$/yr) (0.85 kg $L^{-1}$) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$) (10,000 kcal $kg^{-1}$) (4186 J $kcal^{-1}$); Input flow = 238 kg $ha^{-1}$ $yr^{-1}$ or $9.96 \times 10^{09}$ J/ha/yr.

Note#15 (Seedlings) – Input flow = $2.80 \times 10^{03}$ kg/$ha_{cane}$/yr (Pereira and Ortega, 2010). For emergy intensity estimation, a parallel emergy evaluation of seedlings production was made considering a greenhouse area of 1000 $m^2$ with 70,000 plants/yr produced. Sun ($5.26 \times 10^{12}$ J/yr), steel ($5.00 \times 10^{02}$ kg/yr), PVC plastic ($4.25 \times 10^{03}$ kg/yr), water for irrigation ($2.56 \times 10^{10}$ J/yr), electricity ($3.60 \times 10^{06}$ J/yr) and soil (organic matter; $7.00 \times 10^{04}$ kg/yr) were accounted for, resulting in an emergy intensity of $1.41 \times 10^{11}$ seJ/kg, without accounting for labor and services. The same procedure was made to estimate the energy intensity, reaching a value of $3.78 \times 10^{-02}$ $kg_{eq.oil}$/kg.

Note#16 (Herbicide) – Total herbicide used considering a sugarcane five years cut = 11 kg/$ha_{cane}$ (Macedo et al., 2008). Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = 1.76 kg $ha^{-1}$ $yr^{-1}$

Note#17 (Insecticide) – Total insecticide used considering a sugarcane five years cut = 0.80 kg/$ha_{cane}$ (Macedo et al., 2008). Conversion = (kg/$ha_{cane}$) (1/5 years) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$); Input flow = $1.28 \times 10^{-01}$ kg $ha^{-1}$ $yr^{-1}$.

Note#18 (Enzyme for adjacent plant) – Assuming that sugarcane bagasse has the same characteristics of corn stover, the enzyme consumption in a biochemical conversion is 613 $kg_{enzyme}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{enzyme}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = 86 $kg_{enzyme}$/ha/yr.

Note#19 (Lime for adjacent plant) – Assuming that sugarcane bagasse has the same characteristics of corn stover, the lime consumption in a biochemical conversion is 2395 $kg_{lime}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{lime}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = 336.06 $kg_{lime}$/ha/yr.

Note#20 (Water for adjacent plant) – Assuming that sugarcane bagasse has the same characteristics of corn stover, the water consumption in a biochemical conversion is 186,649 $kg_{water}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{water}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = $2.62 \times 10^{04}$ $kg_{water}$/ha/yr.

Note#21 (Sulfuric acid for adjacent plant) – Assuming that sugarcane bagasse has the same characteristics of corn stover, the sulfuric acid consumption in a biochemical conversion is 3288 $kg_{acid}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{acid}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = 461.36 $kg_{acid}$/ha/yr.

Note#22 (Diammonium phosphate for adjacent plant) – Assuming that sugarcane bagasse has the same characteristics of corn stover, the diammonium phosphate consumption in a biochemical conversion is 154 $kg_{phosphate}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{phosphate}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = 21.61 $kg_{phosphate}$/ha/yr.

Note#23 (Corn steep liquor for adjacent plant; organic nitrogen source) – In Brazil, this source of organic nitrogen could be obtained from other source, but we decided to keep with this source to maintain the same nitrogen balance of Mu et al. (2010). Assuming that sugarcane bagasse has the same characteristics of corn stover, the corn steep liquor consumption in a biochemical conversion is 1232 $kg_{liquor}$/h for a 98,039 $kg_{wet\text{-}biomass}$/h (Mu et al., 2010). Reference for this study for bagasse used in second generation ethanol production = 266,533 $ton_{dry\text{-}bagasse}$/yr; Conversion = ($kg_{liquor}$/h) (h/$kg_{wet\text{-}bagasse}$) ($ton_{dry\text{-}bagasse}$/yr) (1000 $kg_{dry\text{-}bagasse}$/$ton_{dry\text{-}bagasse}$) (2 $kg_{wet\text{-}bagasse}$/$kg_{dry\text{-}bagasse}$) (1/38,750 $ha_{bioref.}$); Input flow = 172.87 $kg_{liquor}$/ha/yr.

Note#24 (Labor) – Labor hours for conventional sugarcane ethanol production in Brazil (Pereira, 2008): Agricultural phase = 0.01183 h/$L_{ethanol}$ of temporary work + 0.00507 h/$L_{ethanol}$ of permanent work; Sugarcane transport = 0.0005 h/$L_{ethanol}$; Industrial phase = 0.0012 h/$L_{ethanol}$. For biorefinery scenario, sugarcane will be totally harvested by machines, thus the temporary work during agricultural phase will not be necessary. Nevertheless, an increase of permanent workers during agricultural, transport and industrial phases will be necessary due to increase of harvesters, transport and mill's productivity. For biorefinery scenario, we assumed an increase in 10% on Pereira's (2008) values, except for temporary work on agricultural phase that was disregarded. Reference for this study = 2,945,000 $ton_{cane\text{-}wet}$/yr and 124 $L_{ethanol}$/$ton_{cane\text{-}wet}$; Conversion = [(1.1) (h/$L_{ethanol}$ for permanent work in agricultural phase) + (1.1) (h/$L_{ethanol}$ for transport phase) + (1.1) (h/$L_{ethanol}$ for industrial phase)] ($ton_{cane-wet}$/yr) ($L_{ethanol}$/$ton_{cane-wet}$) (1/38,750 ha); Input flow = 70.18 h $ha^{-1}$ $yr^{-1}$

Note#25 (Services) – Services for current ethanol plant = 365 USD/ha/yr (Pereira and Ortega, 2010). It was assumed an increase in 10% of services value for Biorefinery scenario; Services include taxes and private services; Negative externalities = 230 USD/ha/yr (Pretty et al., 2005); Conversion = [(1.1) (365 USD/ha $_{bioref.}$/yr)] + [(230 USD/$ha_{cane}$/yr) (31,000 $ha_{cane}$/38,750 $ha_{bioref.}$)]; Input flow = 585.5 USD/ha/yr.

Note#26 (Ethanol) – Ethanol produced by conventional mill = 91 L/$ton_{cane-wet}$; Ethanol produced by adjacent plant = 33.48 L/$ton_{cane-wet}$ (Seabra and Macedo, 2011); Reference for this study = 2,945,000 $ton_{cane-wet}$/yr; Conversion = [(91 L/$ton_{cane-wet}$) + (33.48 L/$ton_{cane-wet}$)] (2,945,000 $ton_{cane-wet}$/yr) (1/38,750 $ha_{bioref.}$); Output flow = 9461 L $ha^{-1}$ $yr^{-1}$.

Note#27 (Electricity) – Electricity demanded for biorefinery internal processes = 28 kWh/$ton_{cane-wet}$; Electricity produced by conventional mill = 32 kWh/$ton_{cane-wet}$; Electricity produced by adjacent plant = 17.75 kWh/$ton_{cane-wet}$ (Seabra and Macedo, 2011); Reference for this study = 2,945,000 $ton_{cane-wet}$/yr; Conversion = [(32 kWh/$ton_{cane-wet}$) + (17.75 kWh/$ton_{cane-wet}$) – (28 kWh/$ton_{cane-wet}$)] (2,945,000 $ton_{cane-wet}$/yr); Output flow (surplus electricity) = 64,053,750 kWh $yr^{-1}$.

Note#28 (Water infiltration) – Rainfall of 1.4 $m^3$ $yr^{-1}$ (http://www.sigrh.sp.gov.br). Brazilian Federal laws establish that 20% of total area of a property must be preserved (it is called as Legal Reserve, LR), added to Permanently Protected Areas (APP, i.e. buffer on rivers, wetlands and water springs). Thus, it was assumed that total area with preserved natural vegetation corresponds to 20% of total system area: 20% of 38,750 ha = 7750 ha; It was assumed a hydrological balance in which 30% of rainfall in natural vegetation is percolated into the soil; Conversion: (1.4 $m^3$ $yr^{-1}$) (1000 L $m^{-3}$) (10,000 $m^2$ $ha^{-1}$) (7750 $ha_{forest}$/38,750 $ha_{bioref.}$) 0.3; Output flow = 840,000 L $ha^{-1}$ $yr^{-1}$

Note#29 (Potential Carbon dioxide absorbed) – The current Brazilian environmental legislation considers that Legal Reserve (LR) and Environmental Protection Areas (APP) (both described in Note#30) can be used only with the purpose to assure the environmental services production, i.e. nowadays agriculture and/or resource extraction practices are totally forbidden in APP areas, but some of those practices are possible in LR areas if there is a sustainability management contract with the Brazilian Institute of Natural Environment and Renewable Natural Resources (IBAMA); that contract is called as "*Contrato de Averbação*", granted only to small family-farms in Sao Paulo State. Thus, those areas with natural vegetation will be able to absorb $CO_2$ from the atmosphere up to when vegetation is still young, until its 50th–100th birthday (it depends on the biome). After that, the natural biome is considered balanced and it is no more able to absorb $CO_2$ (at least at the same ratio than before). If a sustainable use of LR and APP were allowed by Brazilian legislation (i.e. concerning sustainable extraction of old trees to be used in non-burning process of biomass as construction for instance), the net $CO_2$ absorbed in those areas will increase and will not reach steady-state absorption at moderate to long time periods. It was not possible to obtain average values for the age of natural vegetation within systems studied here, so it was not possible to quantify updated values for 2011. Thus, we used the term "potential carbon dioxide absorbed" to represent $CO_2$ absorption by LR and APP areas "if" a sustainable management in those areas were allowed. A Net Primary Productivity for a tropical forest of 925 gC $m^{-2}$ $yr^{-1}$ from Amthor (1998) was considered. Conversion: (925 gC $m^{-2}$ $yr^{-1}$) (10,000 $m^2$ $ha^{-1}$) (7750 $ha_{forest}$/38,750 $ha_{bioref.}$) (1 kg/1000 g) ($kgCO_2$/0.273 kgC); Output flow = 6776 $kgCO_2$/ha/yr.

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