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Comparative analysis of biomass flow in conventional and organic sugarcane production systems: net primary production energy quantification from the agro-ecological perspective

Análise comparativa do fluxo de biomassa em sistemas de produção de cana-de-açúcar convencional e orgânico: quantificação energética da produção primária líquida em uma perspectiva agroecológica

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ABSTRACT: The present study is based on Agroecology principles and follows the theoretical-methodological approach of Social Agrarian Metabolism to find the sustainability biophysical perception in two sugarcane production systems, in Pernambuco State, Brazil, namely: organic and conventional. Data were collected through interviews and subjected to a set of calculations carried out in converters to quantify biomass and energy net primary productivity (NPP) in the two production systems. NPP biomass was decomposed and classified, and it allowed knowing its flow in both production systems. The conventional system recorded a larger amount of socialized biomass and energy, but the organic system accounted for higher total productivity, as well as for proportionally more balanced partition between different biomass and energy categories. The conventional system was energy exporter, and the organic system was energy conservationist. Although the two systems are based on sugarcane monoculture, with biodiversity limitations, the organic system proved to be more sustainable from an agro-ecological viewpoint, since it does not depend on burns, chemical (synthetic) fertilizers and pesticides, and provided biomass and energy to heterotrophic organisms, as well as acted in maintaining background elements and contributed to improve ecosystem services.

Keywords: net primary productivity; agroecosystem sustainability; agroecology; agrarian social metabolism.

RESUMO: O estudo está embasado nos princípios da Agroecologia e utiliza-se do enfoque teórico-metodológico do

Metabolismo Social Agrário para obter uma percepção biofísica da sustentabilidade de dois sistemas de produção de cana-de-açúcar localizados no estado de Pernambuco, Brasil, sendo um orgânico e o outro convencional. Os dados foram coletados por meio de entrevistas e submetidos a um conjunto de cálculos usando-se conversores, de modo a quantificar a produtividade primária líquida (PPL) em termos de biomassa e energia nos dois sistemas de produção. A biomassa da PPL foi decomposta e classificada em categorias, o que permitiu conhecer o seu fluxo em ambos os sistemas de produção. O sistema convencional resultou em maior quantidade de biomassa e energia socializadas, porém o sistema orgânico apresentou maior produtividade total, bem como uma partição proporcionalmente mais equilibrada entre as diferentes categorias de biomassa e energia. O sistema convencional comportou-se como exportador de energia, e o sistema orgânico, como conservador de energia. Embora os dois sistemas estejam assentados na monocultura da cana-de-açúcar, com limitações em termos de biodiversidade, o sistema orgânico demonstrou-se mais sustentável do ponto de vista agroecológico, por não fazer uso de queimadas, de fertilizantes químicos (sintéticos) e agrotóxicos, bem como por fornecer biomassa e energia aos organismos heterotróficos, além de atuar na manutenção dos elementos de fundo e contribuir para a melhoria de serviços ecossistêmicos.

Palavras-chave: produtividade primária líquida; sustentabilidade de agroecossistemas; agroecologia; metabolismo Social Agrário.

1. Introduction

Primary production is the term used in ecology to feature energy accumulation in the form of organic matter produced by autotrophic organisms through the photosynthesis process[1]. Thus, vegetal biomass results from sun light conversion into chemical energy made by plants. This accumulated energy is made available to all other organisms and supports a wide diversity of species living in different ecosystems. This process also supports almost all food webs[2]; therefore, it works as vehicle to transfer solar energy to heterotrophic beings[3] (Guzmán *et al.*, 2014).

The ability of ecosystems to convert solar energy into biomass is called gross primary productivity. However, most of this fixed energy is used by plants in their metabolic processes. This is the reason why the amount of energy really incorporated to plant tissues is known as Net Primary Productivity (NPP); therefore, it represents the difference between the energy produced through the photosynthesis process and that used in respiration for vegetables' metabolic maintenance. NPP can be expressed in terms of accumulated energy (joules/hectare) or of synthesized organic matter (kg/hectare)[4] (Haberl *et al.*, 2014).

NPP is the main basis of the trophic chain, and its appropriation by human society affects the remaining populations of organisms that depend on these same resources (Guzmán *et al.*, 2014). Thus, NPP flow assessments in agrarian ecosystems

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[1] Chemosynthesis is relevant in some very specific ecosystems (ocean floor, hydrothermal events, among others); therefore, it is not of interest when we take into consideration the agrarian metabolism.

[2] The food web of a given community is determined based on how the species' nutritional needs in this community are met through interrelation with other species (Gliessman, 2002, p. 19).

[3] Different from autotrophic organisms, heterotrophic beings do not have the ability to produce their own food.

[4] NPP measures the yearly flow; therefore, it is not equal to the amount of permanent biomass per area unit, which measures the stock at given moment.

are closely related to human appropriation of the net primary production (HANPP). According to Haberl *et al.* (2014), studies about HANPP focus NPP assessment in agro-ecosystems, and they also involve the amount of NPP remaining to other species, rather than just the amount of picked NPP that is used by human beings. This process leads to the importance of taking it into consideration and of quantifying a significant part of the produced biomass that re-circulates in agro-ecosystems and that play essential role in the system's adequate functioning and, consequently, in maintaining countless populations of organisms, rather than just the biomass that has some use or monetary-exchange value for society (Guzmán *et al.*, 2014).

Nevertheless, not all accumulated vegetal biomass accounts for the same ecosystem functions. This aspect reinforces the relevance of having all biomass accumulated by plants within the agro-ecosystem's limits quantified and classified (Soto *et al.*, 2016). In order to do so, NPP can be divided into different categories: socialized biomass (SB), recycled biomass (RBio), reused biomass (ReB), unharvested biomass (UnhB) and accumulated biomass (AB).

According to Guzmán *et al.* (2014), SB is the vegetal biomass (wood, firewood, cereal grains, fruits, among others) appropriated by human society, extracted from the agro-system; in other words, vegetal biomass before being subjected to any industrial processing. RBio is the biomass added to the agro-ecosystem (Guzmán *et al.*, 2014). Seeds and vegetative reproduction organs (tubers, rhizomes, seedlings, among others) are also part of RBio. From society's perspective, RBio can be split into two parts:

a) Reused Biomass (ReB): it is the fraction intentionally given back to the agro-ecosystem by humans; therefore, it demands labor. In this case, vegetal biomass added to the agro-ecosystem is acknowledged by society, such as the case of biomass used as input for products (beef, dairy and eggs) or services' obtainment, such as animal traction and agroecosystem fertilization (green manure, compost, mulch, grout, bio-fertilizers, among others).

b) Unharvested Biomass (unhB): it is the biomass given back to the agro-ecosystem through abandonment. Its return to the agro-ecosystem does not demand any human labor. This is the case of harvest waste that does not get any specific treatment, such as the fraction of pasture that is not consumed by cattle, remnants of fruits and roots that are not recycled by heterotrophic organisms (Guzmán *et al.*, 2014).

UnhB can also be split into unharvested biomass on soil surface (UnhBSS) and into underground unharvested biomass (UGunhB), depending on its location, when it is abandoned. AB, in its turn, is the fraction of biomass that accumulates in the shoot (stem or canopy) and in the roots of perennial species (Guzmán *et al.*, 2014).

Thus, the aims of the present study were to quantify vegetal biomass flow and the energy found in it, as well as to investigate its participation in the herein assessed agricultural production systems, and its categorization based on its role in the biophysical dynamics of these systems. In order to do so, the theoretical-methodological approach of Social Metabolism, which aims at describing the reciprocity and inter-dependence association between society and nature, based on the study of matter, energy and information flow was adopted (González de Molina & Toledo, 2011).

The application of this metabolic focus in the agricultural field is called Social Agrarian Metabolism (SAM), whose approach is closely related to studies on biophysical flows that keep the generation of environmental biomass and services (González de Molina & Toledo, 2011; Menezes Neto *et al.*, 2018). This metabolic focus of agrarian systems is largely used by studies in the agro-ecological field (González de Molina, 2011), because it provides information about agro-ecosystems' functioning in space and time. Therefore, the SAM focus can drive transition processes from the conventional agricultural model to more sustainable agricultural styles (Gliessman *et al.*, 2007).

It is worth highlighting that the present study introduces a distinction between organic and agricultural production systems of agro-ecological basis (Caporal, 2008), since it is possible having organic forms that do not respect all dimensions capable of ensuring long-term sustainability, as well as the ecological and social principles defined by Agroecology (Assis & Romeiro, 2002).

2. Methodology

2.1. Study site featuring

The assessed areas are inserted in the Atlantic Forest biome, in Zona da Mata Sul micro-region (Northeastern Brazil), which is featured by presenting tropical climate, with dry season (Mascarenhas *et al.*, 2005). The research involves two sugarcane production systems, one conventional and another organic, located in Chã Grande and Amaraji counties, respectively (Table 1). The herein assessed conventional production system is a good representative of this agricultural model type, which is used in Zona da Mata Sul region, Pernambuco State. The assessed organic system, in its turn, has well-defined features regarding its productive system, which seeks to value property local resources and to integrate agricultural production to industrial production, in order to give back a consistent business model to the organic cachaça and ecological tourism markets.

2.2. Conventional system

The framer and landowner of the site where the assessed conventional production system was installed in is a technician in agriculture and livestock production; he has worked in sugar and alcohol facilities in his region, besides having more than 20-year experience in sugarcane production. Despite sugarcane trading, family income also derives from agricultural inputs from an agriculture/livestock shop they own downtown Amarali County.

TABLE 1 – Information about counties where the study sites are located in

Information	**County**	
	Chã Grande	Amaraji
Area (km²)	84.848	234.956
Population (inhab.)	21,929	22,910
Altitude (m)	470	290
Mean annual temperature (Co)	22.6	24.5
Mean annual rainfall (mm)	1,310	1,460
Distance from the state capital (km)	82	96

SOURCE: IBGE (2013)

Sugarcane produced in this area was mainly sent to big sugarcane and alcohol production facilities in the herein assessed region. However, according to him, there is an asymmetric association between sugarcane suppliers and production plants, mainly because owners of these facilities control the prices, the weighing system and sucrose content measurements; moreover, they usually take long to pay for the supplied raw-material, and it has strongly penalized farmers in their region.

This production system counted on a sugarcane crop and on an area covered with perennial vegetation, which was a Legal Reservation area within the property selected for the study. Sugarcane implementation started in 5 hectares (ha), at the first assessed year, and it was expanded to 30ha, from the second production year, onwards. The perennial vegetation area (Legal Reserve), in its turn, corresponded to one hectare and remained constant for five years. Thus, the sum of sugarcane production area to the legal reservation area totaled 6 hectares in the first harvest (2011/12), and 31 hectares in the following four harvests (from 2012/13 to 2015/16), as shown in Table 2.

Soil was treated with plowing followed by harrowing. Soil liming accounted for 2,000 kg/ha dolomitic limestone, which was added to the soil with the aid of leveling harrow, thirty days after planting. Fertilization was based on NPK-based fertilizer (12-24-18), which was applied at the aliquot of 250 kg/ha on the foundation and of 250 kg/ha on the coverage, in the following years. Either soil correction or fertilization was carried out based on the owner's recommendations, according to his expertise in sugarcane production, in his region.

SP79-1011was the variety used in sugarcane crop implementation, since it presents maturation and intermediate soil demands, good ratoon sprouting, high sucrose content and low flowering, as main features. Plant top can reach 4m in height, and 5 tillers (on average); its real agricultural yield reaches more than 145 tons of sugarcane per hectare, according to a study carried out in São Paulo State by Tasso Júnior (2007).

2.3. Organic system

The study site where the organic sugarcane production system was installed in counted on a previously degraded area. The sugarcane variety selected by the farmer, according to the most adequate features for cachaça production, was planted for research purposes. The agricultural system was implemented for 5-year cultivation (2011-2016), and it followed the raw-material demand of the sugarcane mill (Table 2). However, perennial species were also introduced in the study site's surroundings for reforestation purposes.

TABLE 2 – Area planted with sugarcane in each harvest under conventional and organic production systems.

Production system	**Cultivated area (ha)**					
	Harvest 2011-12	**Harvest 2012-13**	**Harvest 2013-14**	**Harvest 2014-15**	**Harvest 2015-16**	**Total**
Conventional	6.000	31.000	31.000	31.000	31.000	130.000
Organic	0.840	1.776	3.336	4.536	5.256	15.744

SOURCE: Elaborated by the authors

The soil was prepared with mechanical plowing followed by harrowing. Liming was based on applying 400 kg/ha calcitic limestone, which was added to the soil based on leveling harrowing, 40 days before planting, only in the first year. Fertilization was carried out with organic compound, which was prepared with bovine manure, sugarcane bagasse (deriving from the sugarcane mill) and ashes from bagasse burning in the mill's boiler. The compound was manually distributed by employees, at function 3,000 kg/ha and 2,000 kg/ha in coverage, in the following years. These doses were determined based on recommendations by the agronomist who has provided the consultancy to the producer and who aimed at using waste from the mill's production system.

The farmer in charge of the organic production system has Mechanical Engineering major and is expert in growing green vegetables, since it was his focus before growing sugarcane and producing its derivatives. Sugarcane production has been sent to the family's mill, which is located in the planation area were the family produces cachaça, alcohol, brown sugar lumps, brown sugar, liqueurs, jams and jellies. These products were sold in specialized markets and shops, as well as in the family shop, which lies by the production line. Besides income resulting from the sales of sugarcane derivative products, the family also acts in the eco-tourism sector, which is another source of complementary income.

Bagasse, which is a sugarcane-milling byproduct, was fully reused; part of it was used to generate thermal energy for the industrial process (80%). The remaining fraction (20%) was sent back to the plantation area as organic compound to fertilize the soil.

2.4 Data collection

Sugarcane production data referring to five consecutive harvests (from 2011 to 2016) were herein taken into consideration. This period corresponded to a complete sugarcane crop cycle[5], according to standards set for this region – crop renovation is made every 5 years, since sugarcane yield decreases after each cut.

Besides, it is worth highlighting that the herein assessed production systems were quite different in cultivated-area size, in each harvest, in cultivation management, in use of fertilizers and in agricultural productivity. This process results from different strategies adopted to expand production areas, as well as from different crop conduction and management models.

Biomass production was expressed in mean values per hectare, in order to make it possible comparing the two agricultural production systems. Thus, data about input flows, internal circulation, and material and energy output (related to sugarcane biomass production), as well as about the biomass of adventitious plants and about biomass accumulated in perennial vegetation were taken into account.

Primary data were collected straight from farmers' records; it was done through semi-structured interviews and questionnaires. On the other hand, secondary data were collected through consultation

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[5] After planting, the sugarcane crop is able to support from three to six consecutive harvests, depending on factors such as variety, soil and water management, and climate. The crop is called planted sugarcane in its first cut; as *soca* or second leaf, in the second cut; and as *ressoca* or 9th-order leaf in the other cuts until the last harvest; thus, it completes the planted sugarcane cycle, when a new sugarcane crop is planted (Santiago & Rossetto, 2009).

to scientific studies in this knowledge field (Guzmán *et al.*, 2014; Guzmán & González de Molina, 2015).

2.5 Calculations made for net primary productivity analysis

2.5.1. Net primary productivity quantification

NPP quantification was carried out in the two systems, based on the mean total vegetal biomass produced during the 5-year cycle. Thus, it was possible determining values referring to the produced biomass, either the total vegetal biomass (NPP) or its different parts, which were categorized according to their morphological and functional features. Accordingly, it was possible counting the biomass parts harvested for society's use; the ones that were reused as input for the system itself, roots that remained in the soil and sugarcane waste that was either left on the system or recycled. Moreover, the biomass of adventitious plants was calculated, as well as the perennial vegetation structures.

Biomass quantification led to methodological adjustments in the review by Guzmán *et al.* (2014) about the development of indices and factors that allow converting dry biomass into gross energy values, rather than just allowing the conversion of fresh biomass into dry biomass.

Harvest and root indices were used to determine soil surface and underground biomass, according to the formula below:

→ Harvest index

$$= \frac{\text{Harvested biomass}\,(\text{tree top})}{\text{Total shoot biomass}\,(\text{tree top and leaves})}$$

It regards the biomass of the harvested product (fresh matter) in comparison to the sum of this product to the rest of the shoot biomass at harvest time.

→ *Waste index*:

- Waste:shoot ratio

$$\frac{\text{Waste}}{\text{shoot}} = \frac{\text{waste biomass}\,(kg)}{\text{shoot biomass}\,(kg)}$$

- Waste:product ratio

$$= \frac{\text{waste biomass}\,(kg)}{\text{product}\,(kg)}$$

(expressed in fresh biomass)

Waste index calculation for the conventional system took into consideration the burns taking place in the sugarcane crop before the harvests that have generated a large waste loss. This waste rate was added to sugarcane tips (flag leaf), which were ruled out at the cutting time, since the industry is not interested in acquiring them, because of their low sucrose content. Thus, the rate of 5% harvested biomass was estimated for waste index, according to data provided by the farmer (Table 3).

With respect to the organic system, 49% harvested biomass was the attributed waste index, because there were no burns. Thus, the waste index reached 33% in comparison to plant's total biomass area (Table 3).

Data used in the research to set the harvest and waste indices of the production system with, and without, burns followed information provided by Carvalho (2015), whose numbers were quite close to data used by Guzmán *et al.* (2014).

TABLE 3 – Harvest and waste indices recorded for sugarcane culture

Production system	**Harvest index**	**Waste index**		**References**
	(%)[1]	Shoot (%)[2]	Product (%)[3]	
Without burns	67	33	49	Carvalho (2015)
With burns	95	5	5	Carvalho (2015)

LEGEND:

[1] Main product (treetop, in Kg)/shoot biomass

[2] Waste (Leaves and tips, in Kg)/shoot biomass

[3] Waste (leaves and tips, in Kg)/main product (Treetop, in Kg).

SOURCE: Elaborated by the authors

→ *Root index*

- Root biomass:shoot biomass ratio

$$= \frac{\text{Root biomass ratio}}{\text{Shoot biomass}\left(\text{tree top} + \text{leaves}\right)}$$

Data of Brazilian sugarcane crops were used to calculate the sugarcane root index (Vasconcelos, 2002) (Table 4). Besides, data of adventitious plants' root index (Faroni, 2004) and of perennial vegetation were calculated (Almagro *et al.*, 2010).

TABLE 4 – Sugarcane root, adventitious plants and perennial vegetation indices

Vegetation type	**Root index**	**References**
	Shoot biomass/ root biomass ratio (% dry matter)	
Sugarcane	18	Vasconcelos (2002)
Adventitious plants	80	Faroni (2004)
Perennial vegetation	20	Almagro *et al.* (2010)

SOURCE: Elaborated by the authors

According to Vasconcelos (2002), the mean association – expressed in mean tons of dry matter per hectare – between root (3.8 t/ha roots + 1.8 t/ha rhizomes) and the shoot systems (treetops and tips = 27 t/ha and leaves and straw = 5 t/ha) - ranges from 5.6 to 32, and it corresponds to 0.174 or 17.5%.

→ *Biomass of adventitious plants*

The adventitious flora comprises spontaneous plants; it regards the NPP fraction that was not cultivated, that has exerted ecosystem functions (Guzmán *et al.*, 2014). Its estimate reached 2% in the conventional system; part of this vegetation was taken back to the soil after being desiccated with herbicide application. As for the organic system, the 20% index was taken into account in comparison to the sugarcane production. This value was estimated according to the testimony by the farmer and adjusted based on data found in Guzmán *et al.* (2014).

→ *Total Biomass of the sugarcane culture*

Total biomass regards the set of biomass produced in sugarcane crops, based on agricultural production, summed to the biomass of adventitious plants:

$$\text{Total biomass} = \text{sugarcane biomass} + \text{spontaneuos biomass}$$

→ *Fresh biomass conversion into dry biomass*

Fresh biomass was turned into dry biomass through conversion indices in Table 5. Dry matter content used for harvested sugarcane reached 30%, and the used content of dry mater for the waste recorded 50% (Pierossi & Fagundes, 2013).

TABLE 5 – Index of sugarcane fresh matter conversion into dry matter

Conversion index	Shoot (%)	Shoot (%)	References
	Harvested	Waste	
Dry matter content (DM/FM)	30	50	Pierossi & Fagundes (2013)

SOURCE: Elaborated by the authors.

→ Biomass conversion into gross energy

The collected data were categorized and provided information about the produced energy, which was represented and classified as biomass. The International System Unit Joule (J) was adopted for the study, as well as its multiples, mainly megajoules (MJ) and gigajoules (GJ); 4.1868 J corresponded to 1.0 calories.

Gross energy was found based on information on biomass chemical-bromatological composition (Guzmán *et al.*, 2014). It is the energy released as heat when an organic substance is fully oxidized to carbon dioxide and water (Joules/gram). Gross energy values recorded for the harvested, waste and root biomasses were calculated based on data collected in the study by Leal (2010) and Hassuani (2005). Thus, it was possible determining the energy conversion factors based on sugars' energy values, and on bagasse fiber and straw composing sugarcane biomass (Table 6).

TABLE 6 – Energy conversion factor of sugarcane biomass components

Sugarcane biomass	Energy conversion factor (MJ/kg)	References
Harvested	17.16	Leal (2010); Hassuani, (2005)
Waste	17.85	Leal (2010); Hassuani, (2005)
Root	17.57	Leal (2010); Hassuani, (2005)

SOURCE: Elaborated by the authors.

Harvested biomass of straw's top and tip were selected to determine energy conversion factors like water, sugars and fibers (bagasse), besides mineral salts related to sugarcane plant shoot. It was done because the tip was not used in industrial processing, different from the top. Bagasse recorded 90% top and 10% tip (Carvalho, 2015).

Rates of each component in these parts (harvested and waste) related to the respective energy value were calculated to find sugarcane gross energy (Table 7).

Conversion factors in sugarcane biomass energy components were calculated by the present authors based on data about the work of their respective energy contributions, as shown in Table 8.

It is worth highlighting that these conversion factors can be influenced by the variety's genotype, by hormonal regulation in each plant, phenotype status and growth conditions (climate, soil, inter- or intra-species' competition, cultural practices, among others).

2.5.2 Net primary productivity categories

TABLE 7 – Shoot fresh matter in sugarcane culture

Shoot fraction	Fresh matter		References
	Quantity (kg)	Moisture content (%)	
Plant top (harvested biomass)	67	70	Carvalho (2015)
Leaf	19	40	Carvalho (2015)
Plant tip	14	60	Carvalho (2015)
Total	100	-	

SOURCE: Carvalho (2015).

TABLE 8 – Energy factors of sugarcane biomass components

Biomass components	Quantity (kg/t)	Rate (%)	Gross Energy (MJ)	Energy conversion factor (MJ/kg)
Sugars	150	35	2.500	16.67
Fiber (bagasse)	135	32	2.400	17.77
Straw (leaves)	140	33	2.500	17.85
Total	**425**	**100**	**7.400**	**17.41**
Harvested biomass	271.5	-	4.660	17.16
Waste	153.5	-	2740	17.85

SOURCE: Leal (2010); Hassuani (2005).

Social Agrarian Metabolism focus is based on Agroecology principles (González de Molina, 2011; Guzmán *et al.*, 2014; Tello *et al.*, 2015) that recommend NPP partition into different categories to best know the matter and energy flow either in the fraction destined to society or in that reused in agro-ecosystems. Thus, the following biomass categories set for the NPP of the herein assessed systems were used according to the methodological path designed for the present study (Menezes Neto *et al.*, 2018):

Socialized Biomass (SB): vegetal biomass chosen in sugarcane plant top; it was destined to industrial processing;

Recycled Biomass (RBio): it was divided into:

Reused Biomass (ReB): sugarcane bagasse biomass used in the compositing process; reproduction material (cuts of harvested stalks that were used to expand the planting area), sugarcane leaves and straw; plant tips (leaves) and vegetal waste of adventitious plants' shoot weeding.

Unharvested Biomass (UnhB): it was divided into:

Soil surface (UnhBSS): No

Underground (UGUnhB): sugarcane culture roots and roots of adventitious plants;

Accumulated Biomass (AB): shoot structure biomass (stem and plant top) and roots of native perennial plants.

3. Results and discussion

3.1. Sugarcane biomass yield analysis

The amount of dry matter of biomass harvested from sugarcane shoot under the conventional system was quite bigger than that of the organic system (Table 9). However, when the comparison was based on total dry matter, the organic system exceeded the conventional one. It was mainly explained by the great contribution by agricultural sugarcane waste biomass left on the soil in the organic system; the conventional system, in its turn, had this fraction subjected to burning before harvest.

TABLE 9 - Sugarcane dry biomass under conventional and organic systems – 5-year average.

Production system	Shoot				Roots		Total dry matter (t/ha)
	Harvested		Waste				
	Dry matter (t/ha/year)	(%)	Dry matter (t/ha/year)	(%)	Dry matter (t/ha/year)	(%)	
Conventional	17.60	78	1.47	7	3.36	15	22.42
Organic	11.19	47	9.14	38	3.59	15	23.91

SOURCE: Elaborated by the authors

However, the low yield of sugarcane harvested in the organic system was clear, since it recorded mean yearly result of 11.19 t/ha/year of dry matter. This value was quite below that found for the conventional system when it comes to harvested dry matter, which presented harvest yield of 17.60 t/ha/year of dry matter (Table 9).

These results correspond to the yield of sugarcane harvested in natura (58.65 t/ha/year) in the conventional system and in the organic system (37.29 t/ha/year.) These yield values recorded for the organic system resulted from the farmers' option to prioritize the use of a genetic material that is not so productive, but that records higher efficiency and quality in the cachaça manufacturing process. In other words, in this case, besides agronomic features, sugarcane variety must present the appropriate features for the mill's industrial aim. It is so, because the main goal of the assessed organic system's agricultural production lies on providing raw-material for organic cachaça manufacturing with high quality standards, different from that of the conventional system, which aims at producing bulk material to big alcohol and sugar facilities in the region.

Nevertheless, these mean sugarcane yields are not different from values observed in other Northeastern and Rio de Janeiro State counties, where yield reaches 40 t/ha, on average. However, this value is still much lower in some counties, in São Paulo, Paraná, Minas Gerais and Goiás states, whose yield reaches 120 t/ha of harvested sugarcane, or even more, depending on sugarcane crop age (Ipea, 2016).

The perennial vegetation biomass accumulated in the organic production system was 23% higher than that in the conventional system (Table 10). These data reflect the outcome of efforts done in the organic system to recover areas under advanced degradation state that were unable to support agricultural activities. This factor has clearly helped the re-emergence of water mouths in the assessed property, significant increase in local fauna, increase in soil quality, as well as improved local micro-climate balance. All these elements have led to the use of these areas for visitors' trails and tracks; they often visit the location for educational and touristic reasons.

The conventional system also stood out for the small contribution by biomass produced by adventitious plants in comparison to that of the organic system (Table 10). This finding is related to the fact that herbicide was used to control adventitious plants, in association with regular burns in the conventional system, over the time-period of 5-year cultivation. Both practices decrease the adventitious plant content in conventional sugarcane crops. This process has negative effect, because it rules out most of the vegetal biomass that could be reused to improve the agro-ecosystems' fertility, rather than just to increase the amount of unharvested biomass waste, which is a relevant source of food for wild animals and of local biodiversity. Consequently, adventitious plants' reduction stops their roots from contributing to soil chemical, physical and micro-biological enhancement.

On the other hand, the organic system does not use herbicides or burns, so the contribution by adventitious plants' biomass is quite significant. It corresponded to 13% of the NPP, whereas this value, in the conventional system, only recorded 3%. It was also possible observing higher perennial vegetation biomass ratio in the organic system (11%) in comparison to the conventional system (Figure 1).

TABLE 10 – Dry biomass of adventitious plants under conventional and organic system – 5-year average.

Production system	**Shoot**		**Roots**		**Total dry matter (t/ha)**
	Dry Matter (t/ha)	Rate (%)	Dry Matter (t/ha)	Rate (%)	
		Adventitious plants			
Conventional	0.35	56	0.28	44	0.63
Organic	2.24	56	1.79	44	4.03
		Perennial plants			
Conventional	19.92	83	4.08	17	24.00
Organic	26.09	83	5.34	17	31.43

SOURCE: Elaborated by the authors

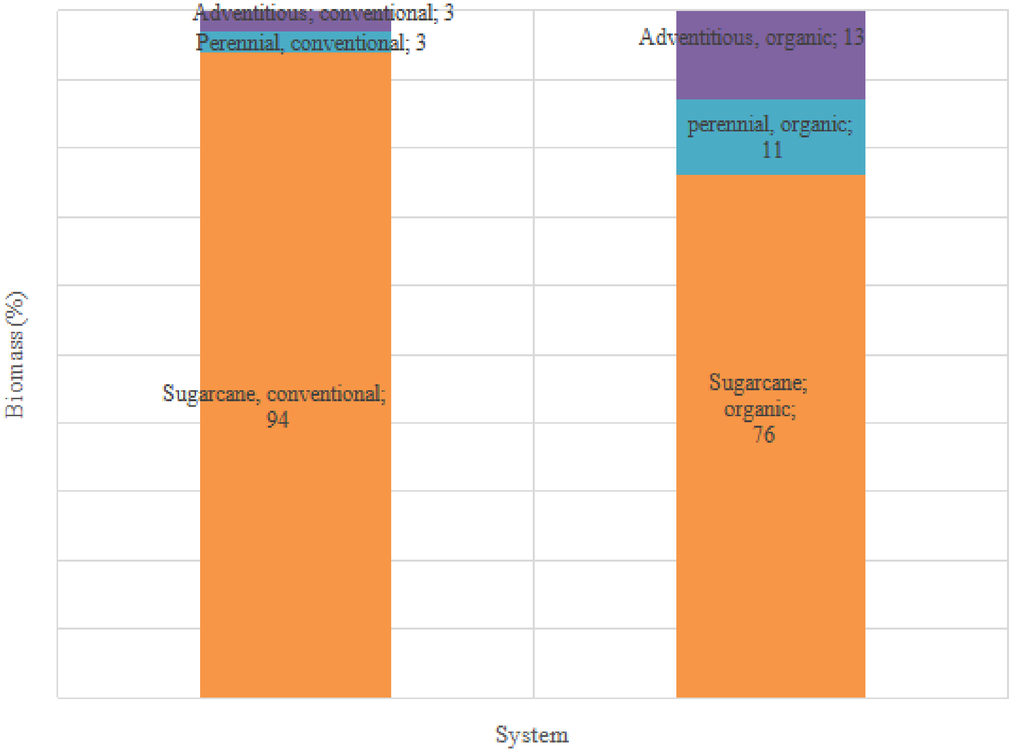

FIGURE 1 – Net primary productivity distribution into vegetation types in conventional and organic sugarcane production systems.
SOURCE: Elaborated by the authors

With respect to the conventional system, some factors, such as irrigation, dense planting, intensive use of fertilizers and soil amendments, have favored the highest yield indices in comparison to the organic system.

However, if one has in mind the temporary increase in yield caused by the use of synthetic fertilizers, it is possible stating that these products demand high energy costs to be manufactured; moreover, it can cause serious losses to local biodiversity.

Therefore, it is recommended to such a strategy to be avoided by using techniques aimed at reducing losses, but also by using green fertilization, organic compounds or even nitrogen biological fixation, based on using legumes (Pelletier *et al.*, 2011).

3.2 Gross sugarcane energy yield analysis

The gross energy yield recorded for the material harvested in the conventional system exceeded by more than 50% that recorded for the organic system, given the huge difference in agricultural yield between these two systems. However, it was possible observing that the total energy of the organic system was 8% higher than that of the conventional system (Table 11), mainly because this system had ruled out most of the straw waste due to the burns before harvest.

Thus, the ratio between harvested biomass gross energy (46%) and the other fractions of the assessed vegetables in the organic system, i.e., shoot (39%) and root (15%) waste, was more balanced, although the gross energy ratio was uneven in the conventional system, because shoot biomass energy accounted for 78% of the total gross energy in comparison to the other vegetal materials related to sugarcane cultivation, such as shoot (7%) and root (15%) waste. These 78% gross energy recorded for the harvested shoot biomass refers to the fraction that left the system to be used by society (Table 11).

However, energy output at that magnitude order can have negative consequences to sustainability in this production system. This finding indicates, in a certain extent, the growing need of providing nutrients that were removed from the soil by the harvested plants, as well as the restriction of requirements that contribute to local ecological balance. Thus, if the amount of remaining energy in an agro-ecosystem is reduced, the number of species in it will also drop down, and it will have negative impact on its biodiversity. Therefore, for this system not to collapse, the energy that has left the system, in the form of agricultural production, must be recovered, and the limits for maintenance capability must be set, either for humans or for all heterotrophic populations that depend on these same resources (Guzmán *et al.*, 2014).

Moreover, the low energy values attributed to the shoot and root waste of sugarcane produced under the conventional system, in association with adventitious plants' low total energy (Table 12), can compromise the background element maintenance mechanisms[6] (soil, water, biodiversity, among others) forming them and, consequently, the ability

TABLE 11 – Sugarcane gross energy under the conventional and organic systems – 5-year average.

Production system	**Shoot**				**Roots**		**Total Energy (GJ/ha/year)**
	Harvested		Waste				
	Gross energy GJ/ha/Year	(%)	Gross energy GJ/ha/Year	(%)	Gross energy GJ/ha/year	(%)	
Conventional	301.95	78	26.17	07	59.02	15	387.15
Organic	192.03	46	163.10	39	63.05	15	418.18

SOURCE: Elaborated by the authors.

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[6] Background elements are bodies or structures that turn input flows into output flows at a given time scale. Background elements, in agro-ecosystems, demand a specific amount of energy for reproduction and maintenance; it can only be partly replaced by external energy (Guzmán & González de Molina, 2015; Guzmán et al., 2017).

of this productive system to generate ecosystem service flows (Guzmán *et al.*, 2017). Only biomass can feed food chains that support life in the soil and agro-ecosystems' general biodiversity, for example.

From the agro-ecological viewpoint, these results (Table 12) corroborate the sense of energy superiority of the organic system in comparison to the conventional system, because it shows that the organic system has overcome, by more than four times, the production of perennial vegetation's gross energy in the conventional system, as shown in Figure 2.

Furthermore, it is worth highlighting the likely hard time of the conventional system to naturally replace the exported nutrients, because the biomass amount left in the system was low. This process interferes with species' biodiversity maintenance, with soil quality, as well as with the supply of essential environmental services for production system sustainability maintenance.

TABLE 12 – Gross energy of adventitious and perennial plants under conventional and organic systems – 5-year average.

Production system	**Shoot**		**Roots**		**Total Energy (GJ/ha/year)**
	Gross energy (GJ/ha/year)	Rate (%)	Gross energy (GJ/ha/year)	Rate (%)	
			Adventitious plants		
Conventional	6.18	56	4.95	44	11.13
Organic	39.32	56	31.45	44	70.77
			Perennial plants		
Conventional	11.64	83	2.45	17	14.09
Organic	50.66	83	10.64	17	61.30

SOURCE: Elaborated by the authors

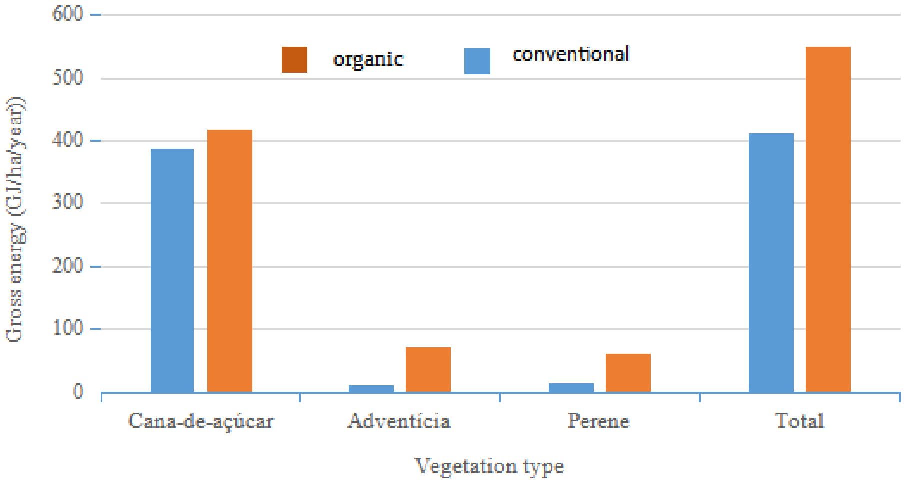

FIGURE 2 – Gross energy yield under the conventional and organic production systems.

SOURCE: Elaborated by the authors.

3.3 Matter and energy flow analysis

Socialized biomass production was higher in the conventional system than in the organic one (Figure 3). However, the opposite was observed for reused biomass, unharvested and accumulated underground biomass. This finding has reflected on the superiority of total NPP in the organic system.

The superiority of the organic system in terms of circulated biomass partly results from the fact that approximately 20% of the sugarcane bagasse was taken as reused biomass from the second cultivation year, onwards. The same happened with the propagation material that was produced in the property and used to enlarge the cultivation areas in the following years; thus, it also returned to the system as reused biomass.

Exceptions were observed in unharvested biomass, whose value in both systems was zero (0), because this fraction was burned in the conventional system and redistributed in the organic one. In other words, as for the current study, ashes from burns in the conventional system were disregarded, from the energy viewpoint, but the shoot material acted as dead material in the organic system and became part of the reused biomass. These data are important when they are related to effects on local biodiversity, since this unharvested material is a necessary source of food for the local wild fauna.

Socialized biomass represented 70% of the biomass produced in the conventional system and 31% of it in the organic system, respectively (Figure 4). This number corresponds to the largest part of the vegetal material that was produced under the conventional system and that left the system. As for the organic model, it recirculated and/or was accumulated in the agro-ecosystem. This process has straight consequences on the system's structure, although in different ways. It is so, because such negative effects on the conventional system, like soil nutrient losses and reduction in the energy available for the trophic chain, meant positive effect

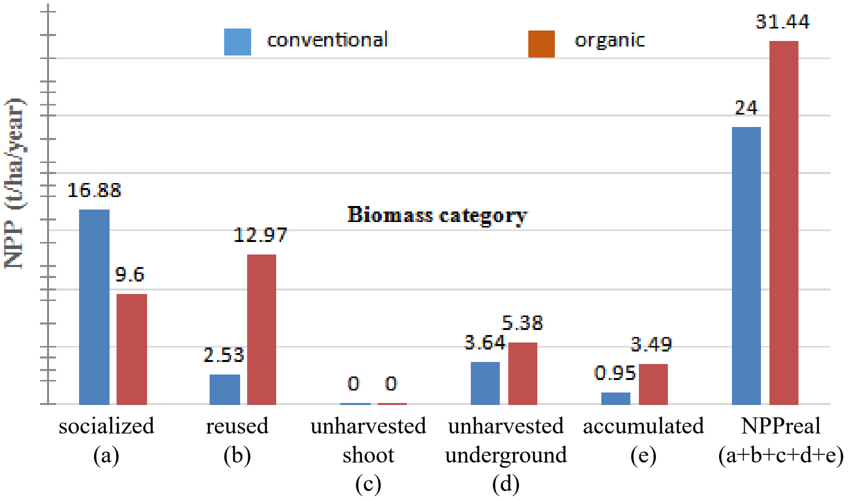

FIGURE 3 – Sugarcane net primary productivity partition in the conventional and organic systems.

SOURCE: Elaborated by the authors.

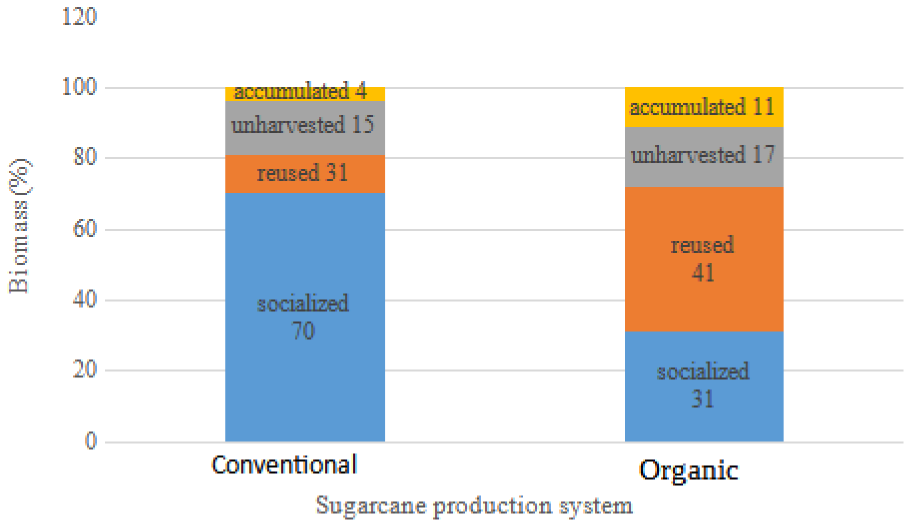

FIGURE 4 – Rate of sugarcane net primary productivity biomass categories under the conventional and organic systems.
SOURCE: Elaborated by the authors.

on the organic system, due to its lower dependence on external inputs for soil fertility and ecological balance in the agricultural system. Moreover, this larger fraction of reused and underground unharvested biomass that recirculated in the organic system implied in boosting its ecosystem functions and the socio-metabolic dynamics, as a whole.

Sugarcane socialized biomass was closely related to the balanced agricultural vegetation, with low biological biodiversity, because, overall, there is no ecological structure for many living beings to live in a mono-cultivation sugarcane crop. Another study has developed and applied sustainability indicators for these same agro-ecosystems (Menezes Neto *et al.*, 2017); they showed environmental dimension limitations in both production systems, mainly because they adopt the sugarcane monoculture model. Nevertheless, these effects from mono--cultivation have reflected differently on different systems. As for the conventional system, its larger fraction of socialized biomass was associated with the intense use of irrigation, fertilizers and herbicides. With respect to the organic system, where there was no application of synthetic fertilizers, neither of herbicides, there were the right conditions for some adventitious plants to coexist with the agricultural culture. It is possible considering that negative impacts over biodiversity were minimized in the organic system, in comparison to the conventional system.

Thus, the application of fertilizers rich in organic matter, in the form of compounds, and the use of some conservation practices in the organic system, such as dead coverage, have benefited soil micro-fauna and important services for vegetal maintenance, by increasing edaphic biodiversity. Biomass accumulated in the perennial vegetation, in its turn, provided the right conditions to favor grater biodiversity and, consequently, more environmental services. This process involves increasing the number of natural enemies that control agricultural pests by favoring bio-geo-chemical cycles and improving local water regulation.

Table 13 depicts gross energy values, in the form of biomass categories (GJ/ha/year), of the conventional and organic systems. Thus, it was possible calculating the association between the gross energy of sugarcane biomass categories in the conventional system and that of the organic system. Accordingly, it was possible clearly analyzing the ratio, in percentage, between the respective partitions, in both systems.

Data make the superiority of the organic system over the conventional one clear when it comes to biomass production based on energy values. The exception regarded socialized biomass values, which recorded mean yield 117% higher in the conventional system than in the organic one (Table 13). However, this result was reached due to huge energy expenditure with external inputs over the 5-year sugarcane production cycle. Thus, according to comparative results recorded for the two herein assessed systems, it is possible stating that the conventional system behaves more like biomass explorer and external energy consumer, whereas the organic system can be taken as the energy saving system.

Figure 5 shows a diagram with the scheme of energy flow in different biomass categories, in the two analyzed system. It shows the interrelation between nature (agro-ecosystem) and society, which is the very basis of Social Agrarian Metabolism studies.

4. Final considerations

From the market interests' viewpoint, agriculture gained efficiency and productivity due to technical changes that have emerged over modern history. This process met the aim of meeting a growing number of human demands based on appropriating NPP's harvestable fractions. This is the reason why most studies on agricultural energy flow mainly focus on the harvested part of the cultivated plants, whereas root biomass and culture waste is oftentimes ignored.

TABLE 13 – Gross energy of sugarcane biomass categories in the conventional and organic production systems, and the rate of the gross energy of sugarcane biomass categories in the conventional system in comparison to the organic system.

Biomass categories	**Production system**		**Conventional/Organic association (%)**
	Conventional (MJ/ha/year)	Organic (MJ/ha/year)	
NPP_{Real} (a + b + c + d + e)	412.36	550.25	75
Socialized biomass (a)	289.71	163.40	177
Reused biomass (b)	44.59	231.05	19
Unharvested biomass (c + d)	63.97	94.50	68
Unharvested shoot biomass (c)	-	-	-
Unharvested underground biomass (d)	63.97	94.50	68
Recycled biomass (b + c + d)	108.562	325.55	33
Accumulated biomass (e)	14.09	61.30	23

SOURCE: Elaborated by the authors

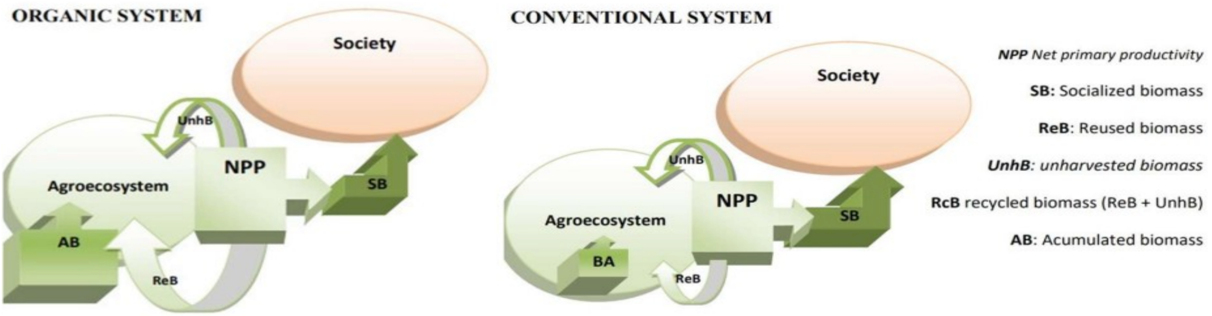

FIGURE 5 – Schematic representation of net primary productivity energy flow in conventional and organic sugarcane production systems.
SOURCE: Elaborated by the authors.

However, when the analysis is made from the sustainability viewpoint, and based on energy efficiency assessment, a larger fraction of NPP flow destined to human consumption can imply in reduced biomass flow inside agro-ecosystems. Thus, the trend of reducing the use of biomass' inner remains becomes unsustainable, because it poses risk to the necessary energy investment in important agro-ecosystems' resources to promote soil fertility (protection against erosion, organic matter increase and increase in the amount of important soil micro-organisms), as well as in biodiversity maintenance and in other ecosystem services. Moreover, NPP is the very basis food chains are built on. Therefore, it establishes maintenance-ability limits to heterotrophic populations found in the system.

Because the unharvested fraction, or the one that is not removed from the agro-ecosystem, has important ecological functions, its quantification must be valued. In order to do so, conversion values that allow calculating the total biomass of sugarcane produced in agro-ecosystems were developed based on production data. These indices also enabled converting fresh biomass into dry biomass, and turning biomass into gross energy values. Yet, conversion factors that have related different plant parts (roots, harvested fraction, shoot) were also created.

Therefore, the methodological path taken in the current study allowed not just quantifying the whole vegetal biomass and the energy found in it, but its categorization in differentiated partitions, according to its role in the biophysical dynamics of the assessed agro-ecosystem.

The present research was substantiated by both Agroecology principles and by the Social Agrarian Metabolism focus for its theoretical-methodological support. This process enabled better understanding the role of each one of the different NPP fractions in agro-ecosystems, be it in the biomass or in the energy form.

Research results have shown that the gross energy yield of the material harvested in the conventional system has exceeded by more than 50% that presented by the organic system. However, when it comes to total dry matter, the organic system has shown the highest yield; its total energy was 8% higher than that observed for conventional system. This finding resulted from the great contribution of sugarcane agricultural waste to the organic system, which also contributed to its perennial vegetation

– it was 23% higher than that of the conventional system, and broadened its ecological benefits.

There was small biomass return to the agro-ecosystem of the conventional model, be it due to little contribution by adventitious plants caused by herbicide application, or to the burning of sugarcane leaves before harvest. This process has led to this system's difficulty in naturally replacing soil nutrients and in keeping local species' biodiversity. In other words, the low energy values attributed to shoot waste, in association with the low total energy of adventitious plants, can compromise the maintenance mechanisms of background elements in this production system and provide essential environmental services for the maintenance of its own sustainability.

Material and energy flows show that biomass supply to society in the conventional system accounted for 70% of the produced biomass, but it was only 31% in the organic system. This finding means that most production in the conventional model left the system, different from the organic system, where most of the biomass recirculated, or was accumulated, in the agro-ecosystem. Therefore, it is possible concluding that the conventional system behaved as energy exporter and consumer, whereas the organic system can be taken as energy-saving system.

The relevance of quantifying NPP was clear, rather than the aim of only considering what is harvested, since knowing other fractions of the produced biomass – which was reused or recycled inside the agricultural production system – allowed better understanding the degree of energy balance inside agro-ecosystems. The ratio between the gross energy of the harvested biomass (46%) and other assessed vegetal fractions was more balanced in organic systems, and more uneven in conventional systems, which had 78% of its total gross energy quantified as harvested biomass. Based on such results, it became possible getting to know and analyzing information about structuring and functional changes capable of affecting the maintenance of ecosystem services likely provided by agro-ecosystems, as well as to identify their limits and potentials. This process can help decision-making about developing more ecologically balanced systems.

Finally, it is important suggesting further studies focused on using the Social Agrarian Metabolism to, among other things, determine energy efficiency indicators for agriculture, either at broader scales, both at regional and national level, or at more complex contexts, such as research on agroforest or polyculture systems, within peasant production units. It must be done to better understand the degree of sustainability of the society/nature relationship. These studies can be carried out based on historical data involving metabolic changes in traditional agriculture to reach the industrialized agriculture, on climate change effects in the field, or even on developing agro-ecological transition propositions focused on reaching higher sustainability standards, either at agro-ecosystem level or at agro-food system level.

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