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Sustainability of urban aquaponics farms: An emergy point of view

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ABSTRACT

Aquaponics is a food production system that aims higher sustainability by integrating advantages gained from aquaculture and hydroponic production. Aquaponics aims to mimic the biological process that happens in the natural environment in a controlled production system. As it can be applied to small scales, aquaponics is considered an important alternative for urban regions, which have low availability of agricultural land and water resources. Furthermore, the advantage is that it is located close to final consumers. Aquaponics has been labeled as an environmentally friendly food production system, but its demand for energy and materials cast doubt on its sustainability. A systemic understanding of aquaponics production systems is needed to determine the magnitude and balance between its potentialities and constraints, in which emergy synthesis appears as a powerful tool for this purpose. This study applies emergy synthesis to assess the sustainability of two different (scale and marketable products) urban aquaponics farms in Brazil, but differently from other emergy studies, ecosystem services and disservices are included in the analysis as an attempt to represent the system performance holistically. Results show that the type of materials used in aquaponics infrastructures has the highest influence on total emergy demand. Surprisingly, electricity and fish feed showed a low influence on the total emergy, reinforcing the idea that aquaponics systems have a more efficiency feeding management than traditional aquaculture systems. Besides producing vegetables and fish, the inclusion of ecosystem services highlights the importance of aquaponics for educational and tourism purposes. Finally, the obtained indicators from modeling scenarios revealed that replacing the water source and some materials deserves priority attention to increase the sustainability of urban aquaponics farms.

1. Introduction

The population of cities has increased substantially over the last decades (UN, United Nations et al., 2018). Urbanization has become a major global trend, and supporting it demands provision systems for infrastructure, logistics, communication, commerce, cultural aspects, tourism, and employment generation (Leamer and Storper, 2014). This expansion is accompanied by greater demand for food associated with supply chains from rural areas (Santos, 2016). However, producing food in rural areas and transporting it to support cities has been reported as one of the key contributors to increased greenhouse gas emissions, biodiversity loss, water pollution, land-use exhaustion, and a host of other environmental impacts (Goldstein et al., 2016). Thus, adopting urban or peri-urban production systems might be an alternative to help provide sustainable urban food consumption and reduce environmental impacts (Schumacher, 1973; Armanda et al., 2019).

To address food supply problems in cities, production systems located in urban centers have been developed. Compared to rural agriculture, growing food in urban areas has some important advantages, such as proximity to markets, fresh food provision, and reduced transport costs (Artmann and Sartison, 2018). Additionally, local food production also has positive effects in reducing negative environmental impacts due to its insertion in urban centers, promotion of the local economy, and strengthening social development (Goldstein et al., 2016). Vegetable production in urban gardens, buildings and/or house roofs, and hydroponic systems are probably the most popular agricultural food production model in urban centers (Rufí-Salís et al., 2020). Aquaculture, the fastest growing livestock activity in recent years (FAO,

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2020), has also followed this trend and developed highly productive technologies for implantation in urban centers. Aquaponics is one of these technologies.

Aquaponics is an integrated food production system that combines fish and hydroponic vegetable crops (Yep and Zheng, 2019). Most aquaponics systems are run in one loop layout where water and nutrients are shared and recirculated between all compartments, i.e., fish tanks, mechanical and biological filters, and the vegetable production bed (Pinho et al., 2021). In an aquaponics system, the wasted nutrients from fish excrete and feed leaching are converted by microorganisms and used as fertilizer for plant production. The transformation of wasted nutrients into plant fertilizers has the potential to reduce the environmental impact of food production by fully utilizing the feed, minimizing the use of non-renewable resources such as industrial fertilizers, and reducing the need for large volumes of water and land (Joyce et al., 2019). Moreover, producing marketable food close to direct consumers and high diversity of vegetables and fish in small areas are also benefits promoted by aquaponics (Proksch and Baganz, 2020).

In addition to production efficiency, aquaponics is also seen as a suitable approach to promote educational and social outcomes (König et al., 2018). For example, Graber et al. (2014) and Junge et al. (2019) showed that aquaponics is a tool for teaching natural science concepts at all school levels, enhancing academic learning and providing students with the possibility of exploring educational skills. Improving the landscape in urban centers and serving as a leisure area open to public visitation have also been described as characteristics that positively impact society and can be considered a benefit of aquaponics (König et al., 2018; Aubin et al., 2019). These outcomes can be considered ecosystem services since aquaponics systems use a natural process to produce food and indirectly generate services that cause a positive impact on society (David et al., 2020). Ecosystem services (ES) are defined as direct or indirect benefits obtained by humans from natural ecosystems, processes, or production systems (MEAMillennium Ecosystem Assessment, 2005). On the other hand, ecosystem disservices (ED) are described as the processes, functions, and aspects resulting in negative impacts on human well-being (Shackleton et al., 2016).

Aquaponics has been labeled an environmentally friendly food production system (König et al., 2016). However, it is highly dependent on electricity and other non-renewable resources to support its need for constant oxygenation, water recirculation, and filtration (Baganz et al., 2020). Commercial aquaponics production may occur in controlled environments such as greenhouses, using high-cost methods and complex equipment demanding electricity. Additionally, filters from aquaponics systems need to be cleaned periodically, resulting in the discharge of nutrient-rich sludge from them into the natural environment (Abusin and Mandikiana, 2020). Although some solutions to reuse the sludge have been investigated, e.g., three-loops aquaponics layouts (Yogev et al., 2016), they are not yet applied in most commercial aquaponics production systems. Aquaponics sludge may cause ecosystem disservices by causing soil pollution, nitrogen leaching, and habitat deterioration (Shah et al., 2019). All these aspects cast doubt on the real sustainability of aquaponics systems.

Understanding all the strengths and weaknesses of aquaponics is necessary to determine the magnitude and balance between its benefits and harms. Sustainability assessments on aquaculture have been widely applied to quantify its sustainability degree, identify problems, and propose solutions (Valenti et al., 2011). Thus, some authors have used life cycle analysis (LCA) to assess the sustainability of aquaponics systems (Forchino et al., 2017; Maucieri et al., 2018; Chen et al., 2020). These studies have shown that the main aquaponics issues are related to its high electricity demand and the high infrastructure and equipment costs. Among other tools for assessing food production sustainability, emergy synthesis deserve attention. This is because emergy synthesis measures the pressure of the production system on the environment by accounting for all the direct and indirect energy required to produce goods or render services (Odum, 1996). Using this method, the natural environment's effort in providing resources and diluting waste is considered under a donor side perspective by recognizing the 'quality' of energy and converting different units of energy flows into solar emjoules, abbreviated as sej (Brown and Ulgiati, 2004). Emergy synthesis is a robust approach to support sustainable development initiatives (Giannetti et al., 2013). Besides being applied in very different production systems, emergy synthesis has already been used to quantitatively evaluate the sustainability of aquaculture production systems (David et al., 2020).

For aquaponics, emergy synthesis could be used to calculate whether its benefits overlap the negative points and guide the management and adoption of public policies to improve urban aquaponics farm sustainability. This study aims to contribute to the advances in the field by (i) investigating the sustainability performance of aquaponics systems using emergy synthesis and (ii) including ecosystem services and disservices in the emergy synthesis to discuss possibilities to better understand, quantify and represent the co-products generated by aquaponics systems.

2. Methods

2.1. Characterization of the aquaponics farms

The farms were chosen based on the study carried out by Portella et al. (2019), who conducted a nationwide data survey to identify Brazilian aquaponics producers and their main management practices. From the database generated by that study, two aquaponics farms were selected (Farms A and B) based on the following criteria: (i) both farms are located in urban centers of the São Paulo State, Brazil; (ii) they operate as coupled aquaponics systems, which means that the water and nutrients are recycled between all units as the aquaculture, hydroponics, and biological filter units are interconnected; and (iii) a complete and reliable database about their technological processes is available.

The evaluated farms differ mainly in the production scale, materials used in the greenhouse structures, and the quantity and variety of products sold. Raw data on materials and energy supporting both farms were obtained by a distance survey on their operational practices, and in situ observation by authors through fieldwork. The period of one year was considered for both data collection and field observations. Long-term solar radiation and meteorological data were obtained from the Integrated Agrometeorological Information Center (CIIAGRO, 2020). The solar transmittance coefficient into the plastic aquaponics greenhouse was assumed to be 0.81 (Sangpradit, 2014). Regarding the infrastructure facilities and equipment used, for those that last for more than one year, the energy input was converted into yearly flow according to their service life (Vassallo et al., 2007). Both evaluated farms have a greenhouse with a retractable structure that allows for opening and closing air circulation. The water used by the farms comes from the municipal supply system, and the differences in the quantities of water used by the farms are due to the different sizes of fish and plant tanks in the systems. The water volume needed to initially fill the tanks, as well as replace losses and evaporation were accounted for. Although the areas of the farms range from 195 to 460 m^2 (Table 1), the input and output values for each system were standardized for an area of 1 m^2 to enable comparisons.

2.1.1. Description of Farm A

Farm A is an aquaponics farm located in the city of Araraquara (238 thousand inhabitants) in Brazil. This farm focuses on the production and commercialization of vegetables. Moreover, it offers courses on aquaponics and environmental preservation. Fig. 1 presents a conceptual model representing the functioning of Farm A under a systemic perspective, including internal processes and relationships, as well as the dependence of external resources and outputs generated. The diagram presented in Fig. 1 was drawn using the symbol language defined by Odum (1996). Farm activities are performed without heavy machines

Table 1
Technical and economic characteristics of the two urban aquaponics farms studied.

Item	Unit	Farm A	Farm B
Greenhouse area	m^2	460	195
Initial water supply	m^3	10	20
Replacement water	m^3/year	76	5.1
Electricity consumption	kWh/year	408	3228
Stocked fish	unit/year	1600	318
Initial average weight of fish	kg/fish	0.015	0.1
Final average weight of fish	kg/fish	NA	0.65
Fish produced	kg/year	NA	190.5
Seedlings	unit/year	24,840	12,000
Feed	kg/year	1022	209
Supplementation (Iron)	kg/year	1.46	0.36
Supplementation (Calcium)	kg/year	NA	28.11
Supplementation (Potassium)	kg/year	NA	7.36
Skilled labor	hour/day	NA	8
Non-skilled labor	hour/day	5	5

NA: Not applicable.

and equipment, and exclusively through the labor of the two owners. The main farm activities are planting seedlings, feeding fish, harvesting, and selling the vegetables produced.

The Nutrient Film Technique (NFT; Maucieri et al., 2019) is the type of hydroponic subsystem adopted, in which suspended gutters are used to accommodate the vegetables. Water is pumped from the sump to a fish tank, and then it goes by gravity through mechanical and biological filters, respectively. From the biological filter, the nutrient-rich water is pumped to the NFT gutters to nourish the vegetables and then returns to the sump by gravity. The filters are cleaned periodically, and the effluents and sludge removed are discharged to the natural environment. The electricity used to supply the aeration and pumping systems comes from the Brazilian national grid. Ethanol is the fuel used in vehicles to transport vegetables to the local market.

A variety of vegetables are produced, including lettuce, chives, parsley, watercress, and mustard, totalizing an average vegetable production of 5520 kg/year. All vegetables are sold for 0.63 USD/unit. The Nile tilapia (*Oreochromis niloticus*) is the fish species reared; however, fish are not sold, and there is no fish harvest during the production cycles. Fish are used only to foment most of the nutrients needed by plants. Considering that the lifespan of fish reared in this situation is variable, and the adopted stocking density is low, the fish output can be considered negligible, thus we did not include the outcomes of this item in the emergy synthesis.

Farm A offers other services apart from vegetable production, such as courses and lectures on setting up and operating aquaponics systems. On average, three courses are given annually, which lasted 8 h each and reaches ~50 people. The physical space of the farm is also open for visitation and received 157 people in the assessed period. Farm A owners consider this to be the maximum capacity of their property in offering courses and receiving visitors.

2.1.2. Description of Farm B

Farm B is located in the center of São Paulo city (12.2 million inhabitants), Brazil, 279 km far from Farm A. Farm B is part of a non-governmental organization aimed to reintegrate people in social vulnerability. The system boundaries of Farm B are defined in the energy diagram presented in Fig. 2, according to the symbol language defined in Odum (1996). Two different hydroponic subsystems are used in Farm B, i.e., NFT and Deep-Water Culture (DWC; Maucieri et al., 2019). In DWC subsystems, vegetables float in hanging support (rafts, panels, boards) filled with nutrient solution. Different to Farm A, Farm B has an anaerobic biodigester, which is used to treat the waste/sludge generated by the system during the production process. As a result, Farm B ceases to discard 255 L/year of sludge and 16.72 kg/year of organic matter in the environment, besides producing 47.6 m^3/year of biogas and 255 L/year of biofertilizer.

Regarding the management of Farm B, two aquaponics specialists are responsible for technical reports, measurements, and improvements on the production system. Another person is responsible for monitoring the water quality parameters and the growth of fish and vegetables. The electricity used to keep the systems running is obtained from an off-grid photovoltaic system. An average of 190 kg/year of Nile tilapia is produced and marketed at 2.50 USD/kg. Lettuces, peppers, basil, chives and mint are the vegetables that are produced at an average total production of 2640 kg/year and sold locally to farm visitors for 0.95 USD/kg. In the period analyzed, Farm B offered two courses and two workshops for students (including middle and high schools and college), social organizations, and the general community. Educational, tourist, and other

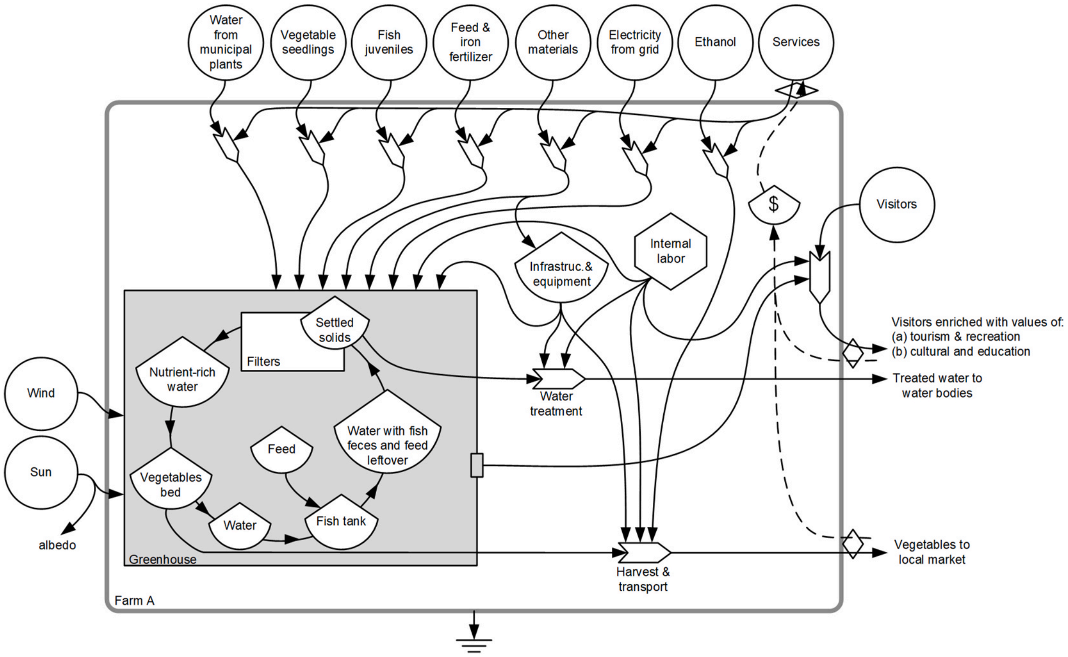

Fig. 1. Energy diagram of the aquaponics system in Farm A.

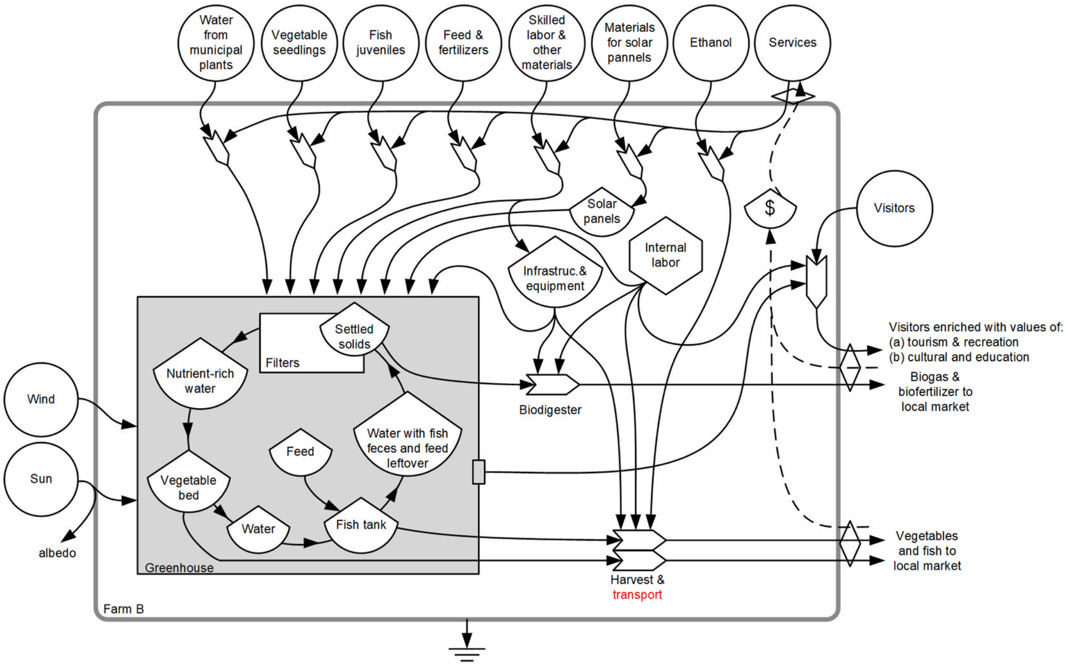

Fig. 2. Energy diagram of the aquaponics system in Farm B.

visitors achieved ~213 people. Farm B managers consider this to be the maximum capacity of the property in offering courses, workshops, and receiving visitors.

2.2. Emergy synthesis

The emergy synthesis is carried out to assess the sustainability of these urban aquaponics farms previously described. The method is performed in four steps described in detail by Odum (1996) and Brown and Ulgiati (2004). First, the system boundaries are defined, and the energy diagram for each farm is drawn. The energy diagram allows us to identify, from a systemic perspective, all energy sources that support the system, internal processes, and its outputs. Second, tables with all the systems' energy inputs (renewable resources, non-renewable resources, and resources from the larger economy) and outputs are built based on the energy diagrams; this is usually called the inventory phase, similar to life cycle assessments (Puca et al., 2017). Third, all input flows are multiplied by their respective unit emergy values (UEVs), mostly taken from the literature, resulting in emergy flows in solar emjoules (sej). UEVs are conversion factors that weigh the importance of different inputs according to their energy quality based on the environmental efforts to make them available. All UEVs used in this study that originated from an outdated database are converted to the 1.20 E+25 sej/year baseline (Brown et al., 2016). All system outputs are considered as co-products, receiving all emergy demanded by the system in calculating their UEVs. Fourth, this step consists of calculating emergy indicators (Table 2) and interpreting them.

In this study, the partial renewabilities of each input are considered for emergy indicator calculations to properly evaluate the system sustainability, as suggested by Ortega et al. (2002) and Agostinho et al. (2008). The inclusion of partial renewabilities is an appropriate approach when the system uses materials and services from the local or regional economy, which could be considered totally or partially renewable. The assumed partial renewability values in this work are based on published scientific papers and are described in the Supplementary Materials.

Table 2
Emergy indicators used in this study.

Indicator	Definition	Formula
Unit Emergy Value	The ratio between the total emergy demanded by the system and the outputs.	UEV = Emergy/Output
Renewability (it includes partial renewabilities)	The ratio between the renewable emergy inputs by the total emergy demanded by the system.	%R = 100*(R + Mr + Sr)/Y
Emergy Yield Ratio	The ratio between the total emergy demanded by the system and the emergy inputs from the larger economy.	EYR = Y/F
Emergy Investment Ratio (it includes partial renewabilities)	The ratio between the non-renewable emergy inputs from the larger economy and the renewable and non-renewable emergy from nature.	EIR = (Mn + Sn)/(R + N + Mr + Sr)
Environmental Loading Ratio (it includes partial renewabilities)	The ratio between the total and imported non-renewable emergy and the renewable emergy inputs.	ELR=(N + Mn + Sn)/(R + Mr + Sr)
Emergy Sustainability Index (it includes partial renewabilities)	Emergy yield per unit of environmental loading.	ESI = EYR/ELR

Emergy indicators according to (Ortega et al., 2002; Brown and Ulgiati, 2004; David et al., 2021), where R: renewable natural resources; N: non-renewable natural resources; F: Resources from the larger economy; Mr: renewable materials; Mn: non-renewable materials; Sr: renewable services; Sn: non-renewable services; Y: total emergy. Suffixes r and n means renewable and non-renewable fraction of material and services.

While the Unit Emergy Value (UEV) is a conversion factor between emergy and output, it is also an emergy indicator that assesses the ecosystem efficiency of the system. UEV measures the amount of emergy used to generate a certain amount of energy. The lower the UEV, the higher the system efficiency. The emergy yield ratio (EYR) indicates the contribution of the process to the economic sector due to local resource exploitation (Brown and Ulgiati, 2004). Renewability (%R) is the proportion of renewable resources in the total emergy used. It indicates the degree of sustainability of a productive system. The EIR identifies whether the use of resources from the larger economy is equivalent to the renewable resources in a production process (Odum, 1996; Brown and Ulgiati, 2004). The ELR indicates the environmental load due to the productive system related to N and F resources demand. ELR values lower than 2 indicate low environmental load, between 3 and 10 indicate moderate environmental load, and greater than 10 indicate high environmental load (Brown and Ulgiati, 2004). The ESI measures how much the production process contributes to the economy in relation to the environmental impact generated, i.e., it indicates the sustainability of the process (Brown and Ulgiati, 2004).

This work goes beyond the current studies by filling a gap in the scientific literature on the sustainability of one emerging aquaculture production system (aquaponics) using emergy synthesis. An innovative way to account for ecosystem services and disservices (ES&D) within emergy synthesis is also proposed and discussed as an attempt to accurately capture the environmental performance for such an important production system (Vassallo et al., 2009; Paoli et al., 2017). ES&D can be considered as co-products of aquaculture production systems, and due to their recognized importance, ES&D should be accounted for in sustainability assessments (Aubin et al., 2019; David et al., 2020). Aquaponics is an agri-aquaculture production system implemented mainly in peri-urban and urban centers. Thus, ecosystem services promoted by aquaponics farms are identified based on data previously published by Aubin et al. (2019) for aquaculture systems and Gómez-Baggethun et al. (2013) for urban agriculture production. In this present study, ecosystem services are accounted for as positive feedback to society, and they are placed in the emergy table as a subitem of the system's outputs. Precisely, the ecosystem services of cultural & educational value, and tourism & recreation values are present in both farms. Due to the lack of databases containing emergy values for these specific environmental services, as well as all issues regarding their quantification in biophysical units, they are quantified according to their monetary value. Thus, for Farm A the annual flows of 'cultural & educational value' and 'tourism & recreation value' are calculated based on how much consumers paid for these services, multiplied by the number of people who attended the courses and visits offered. For Farm B, as this is a non-profit institution that does not charge for the services generated, the annual flows of the services were calculated based on how much they are worth (the same values charged by Farm A), multiplied by the number of people served.

Regarding disservices, as they cause negative feedback to society, the production system should reduce its generation or avoid it, as they could put human well-being and the natural environment in jeopardy. In this present work, disservices are accounted for as an emergy input by including the costs or emergy investment to reduce its potential in causing damage (Shah et al., 2019; David et al., 2020). They are placed in the emergy table as a subitem of the resources from the larger economy, as all energy and materials demanded to implement and operate treatment plants, or other operational management for disservices usually come from the larger economy. As no generic list of specific disservices to aquaculture neither to aquaponics is currently available in the scientific literature, in this work they are identified based on studies that evaluated disservices of agricultural systems (Shah et al., 2019; Yang et al., 2020) and urban productions (Gómez-Baggethun et al., 2013). Farm A generated ecosystem services, since the effluent disposal in the natural environment is a negative aspect that can cause damage to society. Thus, the emergy required to effluent treatment using a biodigester is accounted for as a disservice (represented by the 'water treatment' process in Fig. 1). No disservices generated by Farm B were identified, since it already treats its effluents trough biodigester process. To measure the impact of ecosystem services and disservices inclusion on the emergy synthesis of aquaponics systems, the emergy indicators of Table 1 were calculated with and without ES&D.

2.3. Scenario analysis

Scenario analysis is an important tool to support strategic decision-makers (Postma and Liebl, 2005). Besides, it allows to evaluate how variations in input data affect results, helping farmers to determine actions that could be done in practice to improve the sustainability of aquaculture systems (Häyhä et al., 2011; Li et al., 2011). In the present study, a scenario analysis is performed to assess the effect of changing different input resources (quantity or kind) on emergy indicators. Variables considered within the scenario analyses are those ones that fit the following criteria: (i) inputs that show high representativeness in the total emergy demanded by aquaponics farms; (ii) inputs from non-renewable sources or with low renewability that can be replaced by inputs with higher renewability; (iii) reducing or replacing some inputs that would result in a lower amount of ecosystem disservice generation. The main aim of this scenario analysis is to propose practical alternatives based on the authors' knowledge and the technical-scientific literature to improve the sustainability of the investigated aquaponics systems.

3. Results

3.1. Emergy synthesis of aquaponics Farms A and B

Farm A demanded a 6.3 times less emergy density than Farm B to keep the system running for one year (Tables 3 and 4, respectively). The resources from the larger economy had the highest proportion of emergy inputs in both farms. The materials were the most responsible for this high representation (93% for Farm A and 99% for Farm B). The renewable fraction of the materials used for infrastructure represents 32% of the emergy demanded by Farm A and 37% by Farm B. There is no contribution of natural non-renewable resources (N) for the evaluated farms.

Including ecosystem disservices in emergy accounting does not influence emergy indicators (Table 5). Farm B presents slightly higher renewability (37%) and ESI (0.6) than Farm A (33% and 0.5, respectively). Both farms showed the same value of EYR, while Farm B has a slightly higher performance for EIR and ELR.

Farm B presented a larger variety of output products compared to Farm A (Table 6). UEVs indicate higher efficiency for Farm A in producing vegetables and generating ecosystem services than Farm B as a lower amount of emergy is demanded by Farm A to deliver the same amount of these outputs. Although producing vegetables, fish, biogas and biofertilizer depends on the aquaponics technology adopted, the ecosystem services production depend on the valuation of the courses and visitation and on the physical capacity of each farm to receive people.

3.2. Scenario analysis

Scenario analyses were performed to simulate changes that potentially would improve the emergy indicators of both farms. Water from the municipal grid supply, a resource from the larger economy, was replaced by rainwater, a renewable resource. In this simulation, all the infrastructure needed to collect rainwater, such as gutters, and pipes were considered for Farms A and B. Wood for constructing the greenhouse of Farm A was replaced by iron. The simulation of these variables indicates improvement in the emergy indicators of both farms (Table 7), in which replacing wood by iron in Farm A showed high influence on the new simulated indicators.

4. Discussion

This study intended to assess the sustainability of two urban aquaponics farms in Brazil. It is important to emphasize that both farms used management and structures that are well accepted and adopted in the world of aquaponics. Thus, the results obtained in this paper can be extrapolated and applied to different situations and can assist in the sustainable development of this production system worldwide.

Emergy synthesis of aquaculture production has shown this activity as highly dependent on resources from the larger economy, in which the feed input has the highest influence (David et al., 2020). The materials used to implement the productive systems (infrastructure) were the

Table 3
Emergy table of Farm A.

Note	Item	Unit	Amount (unit/m^2 yr)	UEV (sej/unit)	Emergy (sej/m^2 yr)	Emergy (%)
Renewable natural resources (R)						
1	Sun	J	1.67 E+07	1.00 E+00	1.67 E+07	<0.1
2	Wind	J	1.47 E+06	8.00 E+02	1.18 E+09	<0.1
Total (R)					1.20 E+09	
Non-renewable natural resources (N)						
	None	–	–	–	–	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
3	Ethanol	L	5.89 E+04	4.80 E+04	2.83 E+09	<0.1
4	Water	m^3	9.33E-02	1.92 E+12	1.79 E+11	0.1
5	Electricity from grid	J	2.17 E+06	1.12 E+05	2.43 E+11	0.2
	Materials for greenhouse and production tanks					
6	Cement	g	6.47E-01	3.04 E+12	1.97 E+12	1.5
7	Sand	g	3.00 E+03	1.70 E+09	5.09 E+12	3.9
8	Steel screws	g	2.91 E+01	1.36 E+10	3.96 E+11	0.3
9	Wood	kg	1.89 E+01	1.82 E+12	3.44 E+13	26.5
	Non-renewable materials (Mn)					
10	Ethanol	J	2.51 E+05	4.80 E+04	1.20 E+10	<0.1
11	Water	m^3	9.33E-02	1.92 E+12	1.79 E+11	0.1
12	Electricity from grid	J	1.02 E+06	1.12 E+05	1.14 E+11	0.1
13	Vegetable seedlings	J	9.60 E+06	5.96 E+04	5.72 E+11	0.4
14	Fish juveniles	J	1.09 E+06	7.15 E+05	7.81 E+11	0.6
15	Feed	J	3.22 E+04	9.96 E+04	3.21 E+09	<0.1
16	Iron fertilizer	kg	3.18E-03	1.84 E+12	5.85 E+09	<0.1
	Materials for greenhouse and production tanks					
17	Cement	g	5.85 E+00	3.04 E+12	1.78 E+13	13.7
18	Sand	g	1.25 E+03	1.70 E+09	2.13 E+12	1.6
19	Steel screws	g	8.29 E+01	1.36 E+10	1.13 E+12	0.9
20	Wood	kg	1.11 E+01	1.82 E+12	2.02 E+13	15.6
21	Plastic	g	8.95 E+03	4.19 E+09	3.75 E+13	28.9
	Renewable labor and services (Sr)					
22	Non-skilled labor	J	1.97 E+00	3.27 E+06	6.45 E+06	<0.1
	Non-renewable labor and services (Sn)					
23	Infrastructure and equipment	USD	1.08 E+00	5.60 E+12	6.02 E+12	4.6
24	Non-skilled labor	J	1.10 E+01	3.27 E+06	3.60 E+07	<0.1
25	Fees and taxes	USD	1.63E-01	5.60 E+12	9.13 E+11	0.7
	Ecosystem disservices (D)					
	Materials for a biodigester (Considered as Mn)					
26	Plastic	g	1.77 E+01	4.19 E+09	7.41 E+10	0.1
Total (N + F) [a]					1.30 E+14	
Total (N + F) [b]					1.30 E+14	
Total emergy (Y)						
Without ecosystem disservices (Y = R + N + F) [a]					1.30 E+14	
With ecosystem disservices (Y = R + N + F) [b]					1.30 E+14	
Outputs (O)						
27	Vegetables	kg	1.20 E+01			
	Ecosystem services (ES)					
28	Cultural and education value	USD	3.83 E+01			
29	Tourism and recreation value	USD	3.84 E+00			

Detailed calculation procedures are presented in Table A of supplementary materials.

[a] F = Mr + Mn + Sr + Sn.

[b] F = Mr + Mn + Sr + Sn + **D**.

items with the highest emergy demand for both farms evaluated in this study, a non-expected result from an aquaculture point of view. However, the emergy synthesis of a soil-based vegetable production have shown that greenhouse construction demanded about 57% of the total emergy input (Asgharipour et al., 2020). Economic and life cycle assessment (LCA) studies of aquaponics have also revealed that its infrastructure represents the highest monetary costs and causes the most significant environmental impacts (Forchino et al., 2017; Baganz et al., 2020; Chen et al., 2020; Ghamkhar et al., 2020). These results indicate that regardless of the sustainability assessment method adopted (LCA or emergy synthesis), the employed materials are the main environmental weakness of the current urban aquaponics systems. Therefore, aquaponics seems to reduce the existing issue of low efficiency in the feeding management of traditional aquaculture, because it converts the feed waste into vegetable biomass and minimizes the disposal of nutrient-rich effluents into the natural environment.

The emergy indicators including disservices calculated for the two evaluated aquaponics farms present better performance than most values found for traditional aquaculture production in ponds (Cavalett et al., 2006; Zhang et al., 2011), horticulture (Asgharipour et al., 2020), and soil-based vegetable production (Nakajima and Ortega, 2015) (Table 8). Farm B presented higher renewability than Farm A, probably due to the high renewable fraction and lifetime of iron used in the Farm B greenhouse construction. At Farm A, wood was the primary material used in the greenhouse construction, and consequently, it was responsible for the lower renewability of Farm A mainly due to its low lifetime compared to iron (5 vs. 10 years, for wood and iron respectively). From an emergy perspective, this means that aquaponics systems such as the one used by Farm B tend to be more sustainable in the long run, even though Farm A has shown similar results. This is because production systems with high renewability are more likely to be successful when non-renewable resources become limited (Lefroy and Rydberg, 2003; Brown and Ulgiati, 2004).

The EYR obtained by both farms can be considered low, which means

Table 4
Emergy table of Farm B.

Note	Item	Unit	Amount (unit/m^2 yr)	UEV (sej/unit)	Emergy (sej/m^2 yr)	Emergy (%)
Renewable natural resources (R)						
1	Sun	J	1.51 E+07	1.00 E+00	1.51 E+07	0.0
2	Wind	J	1.61 E+06	8.00 E+02	1.29 E+09	0.0
Total (R)					1.30 E+09	
Non-renewable natural resources (N)						
	None	–	–	–	–	
Resources from the larger economy (F)						
	Renewable materials (Mr)					
3	Water	m^3	6.44E-02	1.92 E+12	1.24 E+11	0.0
	Materials for greenhouse and production tanks					
4	Iron	g	7.88 E+04	3.56 E+09	2.80 E+14	34.1
5	Cement	g	6.47 E+00	3.04 E+12	1.97 E+13	2.4
6	Sand	g	3.00 E+03	1.70 E+09	5.09 E+12	0.6
7	Steel screws	g	2.91 E+02	1.36 E+10	3.96 E+12	0.5
	Non-renewable materials (Mn)					
8	Water	m^3	6.44E-02	1.92 E+12	1.24 E+11	0.0
9	Vegetable seedlings	J	9.85 E+06	5.96 E+04	5.87 E+11	0.1
10	Fish juveniles	J	3.41 E+06	7.15 E+05	2.44 E+12	0.3
11	Feed	J	1.56 E+04	9.96 E+04	1.55 E+09	0.0
12	Iron fertilizer	kg	1.88E-03	1.84 E+12	3.45 E+09	0.0
13	Calcium oxide fertilizer	kg	1.44E-01	1.28 E+12	1.84 E+11	0.0
14	Potassium sulfate fertilizer	kg	3.77E-02	2.23 E+12	8.41 E+10	0.0
	Materials for greenhouse and production tanks					
15	Iron	g	4.63 E+04	3.56 E+09	1.65 E+14	20.1
16	Cement	g	5.85 E+01	3.04 E+12	1.78 E+14	21.7
17	Sand	g	1.25 E+03	1.70 E+09	6.29 E+11	0.1
18	Steel screws	g	8.29 E+02	1.36 E+10	1.13 E+13	1.4
19	Plastic	g	9.39 E+03	4.19 E+09	3.93 E+13	4.8
	Materials for the solar panels					
20	Photoactive materials	g	1.41 E+02	4.38 E+11	6.17 E+13	7.5
21	Glass	g	2.19 E+03	6.08 E+09	1.33 E+13	1.6
22	Copper	g	8.70 E+01	7.75 E+10	6.74 E+12	0.8
23	Aluminum	g	1.41 E+02	4.35 E+09	6.16 E+11	0.1
24	Steel	g	3.33 E+02	9.42 E+10	3.14 E+13	3.8
25	Ethylene Vinyl Acetate	g	7.27 E+01	4.73 E+09	3.44 E+11	0.0
	Materials for the biodigester					
26	Plastic	g	1.71 E+01	4.19 E+09	7.16 E+10	0.0
	Renewable labor and services (Sr)					
27	Non-skilled labor	J	4.66 E+00	3.27 E+06	1.52 E+07	0.0
28	Skilled labor	J	7.45 E+00	2.10 E+07	1.56 E+08	0.0
	Non-renewable labor and services (Sn)					
29	Infrastructure and equipment	USD	1.53 E+01	5.60 E+12	4.39 E+11	0.1
30	Non-skilled labor	J	2.60 E+01	3.27 E+06	8.49 E+07	0.0
31	Skilled labor	J	4.16 E+01	2.10 E+07	8.72 E+08	0.0
	Ecosystem disservices (D)					
	None	–	–	–	–	
Total (N + F) [a]					8.21 E+14	
Total (N + F) [b]					8.21 E+14	
Total emergy (Y)						
Without ecosystem disservices (Y = R + N + F) [a]					8.21 E+14	
With ecosystem disservices (Y = R + N + F) [b]					8.21 E+14	
Outputs (O)						
32	Vegetables	J	1.35 E+01			
33	Fish	J	2.04 E+07			
34	Biogas	J	1.02E-01			
35	Biofertilizer	L	1.39 E+00			
	Ecosystem services (ES)					
36	Cultural and educational value	USD	5.32 E+01			
37	Tourism and recreation value	USD	2.28 E+01			

Detailed calculation procedures are presented in Table B of supplementary materials.

[a] F = Mr + Mn + Sr + Sn.

[b] F = Mr + Mn + Sr + Sn + **D**.

that both farms are highly dependent on resources from the larger economy. This dependence seems to be a trend for traditional aquaculture and vegetable production in soil, which presented values similar to those found in the present study (Table 8). Numerically, this means that the lower EIR value of Farm B indicates better efficiency in using renewable resources (since the evaluated Farms do not demand N resources), where resources are continuously renewed and can supply the production system over a long time. The high EIR value of Farm A indicates that the input of resources from the larger economy is larger than the input of renewable resources. High values (>1) of EIR are generally characteristic of intensive aquaculture systems due to the high need for resources from the larger economy to keep the system running (David et al., 2018).

The ELR showed the same values found for EIR in both farms. This result is related to the non-use of natural non-renewable resources (N) from nature by the evaluated farms. Usually, soil loss (organic matter) is accounted for as an N resource in the emergy synthesis of agricultural production and pond fish farming, but the aquaponics systems have no

Table 5
Emergy indicators with and without ecosystem disservices (ED) for the evaluated aquaponics farms.

Indicator		Farm A		Farm B	
		Without D	With D	Without D	With D
%R	Renewability	32.6	32.6	37.7	37.7
EYR	Emergy yield ratio	1.0	1.0	1.0	1.0
EIR	Emergy investment ratio	2.1	2.1	1.7	1.7
ELR	Environmental loading ratio	2.1	2.1	1.7	1.7
ESI	Emergy sustainability index	0.5	0.5	0.6	0.6

D: Ecosystem disservices.

Table 6
Unit emergy values (UEVs), considering ecosystem disservices (ED), of the outputs produced by the evaluated aquaponics farms.

Outputs	Farm A	Farm B
Vegetables (sej/kg)	1.08 E+13	6.06 E+13
Fish (sej/J)	–	4.02 E+07
Biogas (sej/J)	–	8.01 E+15
Biofertilizer (sej/L)	–	5.89 E+14
Cultural and educational value (sej/USD)	3.39 E+12	1.54 E+13
Tourism and recreation value (sej/USD)	3.38 E+13	3.60 E+13

soil loss, and no other N resource was identified in this study. The ELR of both evaluated aquaponics farms indicated low environmental load, leading to better results for Farm B. This low environmental pressure is similar to values obtained in integrated (Cavalett et al., 2006) and semi-natural aquaculture systems (Zhang et al., 2012), and organic and agroecological horticulture (Nakajima and Ortega, 2015). The lower ELR of Farm B emphasizes the importance of using renewable materials to build the productive structures of aquaponics systems.

The ESI value < 1 presented by both farms are similar to other aquaculture and horticulture systems (Table 8), except for organic and agroecological horticulture, cage and semi-natural pond fish farming. It suggests that evaluated farms provide a low emergy return in relation to their high environmental load generated (Cavalett et al., 2006; Zhang et al., 2012). Aquaculture systems that use a high degree of intensification have shown low ESI values due to high stress generated in the environment to provide the necessary resources to keep production systems running (Odum, 2001; Vassallo et al., 2007; Zhang et al., 2011; Garcia et al., 2014; David et al., 2018).

The emergy indicators obtained for the investigated farms suggest that the sustainability of aquaponics systems relies on materials used in their infrastructure. In general, the aquaponics farms seem to be located at a hierarchical scale similar to those more urbanized or high-tech systems that depend exclusively on F resources. This indicates that, although mimicking natural biological nutrient cycles and maximizing efficiency in resource use, aquaponics strongly relies on F resources that are non-sustainable at principle, unless F resources are produced without adding fossil or other non-renewable energy sources.

Table 7
Emergy indicators of the scenario analyses for Farms A and B.

Indicator	Original values		Simulated values		
	Farm A	Farm B	Water - Farm A	Water - Farm B	Wood - Farm A
%R (%)	32.6	37.7	38.6	37.7	48.0
EYR	1.0	1.0	1.0	1.0	1.0
EIR	2.1	1.7	1.6	1.7	1.1
ELR	2.1	1.7	1.6	1.7	1.1
ESI	0.5	0.6	0.6	0.6	0.9

Detailed calculation procedures are presented in Tables C to H of supplementary materials.

The high UEVs of the products indicate the low efficiency of the aquaponics farms in using the emergy invested in producing food. Nakajima and Ortega (2015) used emergy synthesis to assess conventional, organic, and agroecological systems of vegetable production and found UEVs of 4.29 E+12, 4.34 E+12, and 2.41 E+12 sej/kg, respectively, values much lower than those obtained in the present study for the vegetable production (1.09 E+13 sej/kg for Farm A, and 6.06 E+13 sej/kg for Farm B). However, despite the lower efficiency in incorporating emergy in its products, the aquaponics system adds economic value to the vegetables and fish produced as they are usually pesticide-free and antibiotic-free. Furthermore, it can be stated that, in emergy terms, aquaponics also adds quality energy to the generated products and thus value in more general terms. Aquaponics may cater to a consumer market that demands high-quality fish and vegetables and is willing to pay for the added-value ecological benefits of aquaponics products (Greenfeld et al., 2020). The low efficiency of both farms is even more evident when analyzing the UEVs for fish production. Farm B had low efficiency in fish production when compared to traditional aquaculture systems, such as cages (Garcia et al., 2014; David et al., 2018). Cage fish farming produces tilapias with UEVs ranging from 2.82 E+05 (David et al., 2018) to 1.35 E+06 sej/J (Garcia et al., 2014), lower than the UEV of 4.02 E+07 sej/J of tilapias produced by Farm B. As Farm A does not produce fish for sale, it was not possible to assess its efficiency in tilapia production. These results could be explained by the fact that both farms are not exclusively focused on fish production and their maximum productive capacity is probably not being achieved. Furthermore, in the emergy synthesis of traditional vegetable and fish production (Garcia et al., 2014; Nakajima and Ortega, 2015; David et al., 2018), the emergy costs related to the transport of products from the rural area to the final consumer in the urban area were not considered. Including this emergy cost, which in most cases does not exist in urban aquaponics farms, would possibly equate the UEVs between urban farm products and those produced in rural areas.

More than producing food, both farms promote educational and tourism values by offering workshops, courses, lectures and visits. Farm A was more efficient than Farm B in generating ecosystem services due

Table 8
Comparison of emergy indicators among the results of this study and previous studies of traditional aquaculture and soil-based vegetal production.

Reference	Type of production	Indicator				
		%R (%)	EYR	EIR	ELR	ESI
This study, Farm A	Aquaculture, aquaponics	33	1.0	2.1	2.1	0.5
This study, Farm B	Aquaculture, aquaponics	38	1.0	1.7	1.7	0.6
Cavalett et al. (2006)	Aquaculture, pond fish farming	22	1.3	3.2	3.6	0.4
Zhang et al. (2011)	Aquaculture, cage fish farming	72	1.8	–	0.4	4.6
Zhang et al. (2011)	Aquaculture, pond fish farming	27	1.0	–	2.7	0.4
Zhang et al. (2012)	Aquaculture, semi-natural pond fish farming	65	2.2	–	0.6	4.0
Asgharipour et al. (2020)	Horticulture in greenhouse, soil-based	17	1.0	67.9	76.0	0.2
Nakajima and Ortega (2015)	Organic horticulture, soil-based	42	1.7	1.4	1.4	1.3
Nakajima and Ortega (2015)	Conventional horticulture, soil-based	17	1.2	4.7	4.8	0.2
Nakajima and Ortega (2015)	Agroecological horticulture, soil-based	55	2.2	0.8	0.8	2.8

to its higher capacity in offering courses and receiving visitors. Some studies have shown that aquaponics systems have been considered a production model to promote environmental and financial education (Graber et al., 2014; König et al., 2018; Junge et al., 2019). Besides food production, adding other services to aquaponics systems seems to be a strategy to improve its economic sustainability. The generation of these services can be considered an indirect way to improve the efficiency of the aquaponic systems, as there is no need for an extra emergy input to obtain them, mainly regarding infrastructure. Aquaponics systems in urban centers, depending on the production scale, can also generate ecosystem services such as carbon sequestration, microclimate regulation, and landscape quality improvement. However, due to the small scale of farms and the lack of reliable available data from producers, these ecosystem services were not included in this present study. The inclusion of ecosystem services in emergy synthesis could generate data to help create more accurate public policies (Hein et al., 2013), recognizing the total benefits obtained from aquaponic systems. Public support can be practicable through the payment for ecosystem services (Schirpke et al., 2018; Rodríguez-Morales et al., 2020), offering producers discounts on fees, taxes, or adding value to products through sustainable certifications. Encouraging aquaponics farms in urban centers may be a strategic to obtain multiple benefits (food and environmental services).

Identifying and valuing the ecosystem disservices allowed us to define and measure a strategy to solve the problem before it harms society. Filter cleaning and consequent sludge disposal on the natural environment have been reported as one of the main natural pressures from aquaponics systems (Yogev et al., 2016). This study included the payment for ecosystem disservices regarding the sludge disposal by accounting the emergy demanded for implementing a simple biodigester on Farm A. Since devices such as biodigesters and bioreactors have been tested and have obtained good results for sludge treatments (Khiari et al., 2020), this can be a technically feasible measure to avoid discharging the effluent of aquaponics systems into the natural environment. The use of biodigester by Farm B is a successful example of this strategy because besides demanding less emergy than the treatment process of effluents in Farm A, the biodigester avoided effluent disposal and enabled Farm B to generate biogas and biofertilizer. The use of biodigesters can be considered a strategy to indirectly improve the system efficiency due to generating co-products useful to society; energy obtaining from biogas in this case. Avoiding the generation of ecosystem disservices is a mandatory practice to avoid the negative impacts on society and the natural environment.

Scenario analyses were performed to technically and practically simulate feasible changes that would improve the emergy indicators of both farms. Substituting the water source and replacing the water from the municipal supply system with rainwater resulted in a significant improvement on emergy indicators of Farm A and did not change the indicators of Farm B. Although aquaponics is not a system dependent on a constant water supply, the improvement on indicators was because rainwater is a renewable item with a UEV lower than water treated by the municipal system. Replacing a non-renewable water source with a renewable one shows that this is one of the means to make aquaponics systems more sustainable. Replacing wood with iron when constructing greenhouses also resulted in a considerable improvement in the emergy indicators. This result indicates that adopting materials with high renewability and lifespan is recommended when designing and building aquaponics farms. Simulating these variables (water source and material to build the greenhouse) reveals the potential to obtain better emergy indicators. On the other hand, it is also necessary to think about strategies that improve the system's efficiency, for instance, increasing the productivity of fish and vegetables to achieve its maximum efficiency.

5. Conclusion

We presented the first emergy synthesis of urban aquaponics farms and gave relevant insights to discuss its environmentally sustainable character. The primary purpose of this study was to investigate and compare the sustainability of two urban aquaponics farms using emergy synthesis. The synthesis results showed that the aquaponics farms are highly dependent on resources from the larger economy due to the high emergy demanded by materials (>60%) to build the greenhouses. Despite having lower efficiencies in converting emergy into fish and/or vegetables than traditional agricultural or aquacultural systems found in the literature, both evaluated aquaponic systems presented promising emergy indicators. It should be further noted that urban farms are designed to meet the specific needs of urban centers, i.e., using buildings' dead spots to produce food.

Emergy indicators obtained in this study from simulation can provide subsidies for aquaponics farmers to achieve more sustainable production. Replacing water from municipal treatment plants with rainwater and wood used in the greenhouse infrastructure by iron improved the indicators by up to 40% and proved to be important practical strategies that would bring higher sustainability.

Including disservices should be a standard practice in emergy synthesis to adequately assess production systems. This practice prevents high impacts on system's downstream and would avoid misinterpretations in labeling it as more sustainable without considering a systemic perspective regarding their burden on the environment. Considering ecosystem services allowed to identify that evaluated farms do not focus exclusively on food production, but also on generating educational and tourism values. Recognizing the importance in accounting for ecosystem services could have practical implications for developing public policies such as the payment for ecosystem services, which would support the permanence of these production systems more aligned with sustainability, as suggested by UN Agenda 2030.

CRediT authorship contribution statement

Luiz H. David: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Sara M. Pinho:** Conceptualization, Investigation, Writing – original draft. **Feni Agostinho:** Conceptualization, Methodology, Writing – review & editing. **Jesaias I. Costa:** Data curation. **Maria Célia Portella:** Writing – review &; editing, Visualization. **Karel J. Keesman:** Writing – review &; editing, Visualization. **Fabiana Garcia:** Conceptualization, Writing – review &; editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

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