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Environmental accounting of the yellow-tail lambari aquaculture: sustainability of rural freshwater pond systems

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Abstract

Freshwater pond aquaculture is the prevailing fish culture system worldwide, especially in developing countries. Climate change outcomes and inadequate environmental practices challenge its sustainability. This study applies emergy synthesis to assess the environmental performance of freshwater pond aquaculture in Brazil, aiming to identify and propose practices towards sustainability. As a study model, nine semi-intensive lambari farms operating at three levels of management were evaluated: low (LC), moderate (MC) and high (HC) control. Results showed that the main inputs for LC were services (27-46%), feed (7-39%) and water (15-21%), while for the MC and HC farms, they were feed (35-49% and 17-48%, respectively) and services (33-39% and 26-36%, respectively). All farms required more than 60% of their emergy from purchased inputs, resulting in low emergy sustainability index (ESI = 0.1-0.5). Replacing animal protein and oil on diet composition by vegetal sources, using superficial water instead of springwater, increasing juvenile productivity, and controlling pond fertilization can lead all systems to higher efficiency and resilience, increasing sustainability.

Keywords: rural aquaculture; water use; emergy; fish production.

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1. Introduction

The sustainable development was stated as a fundamental goal in the ecosystem approach to aquaculture (EAA) proposed by FAO in 2008 [1], and it remains a major concern [2,3]. Discussions on the sustainability of aquaculture have focused on the assessment of different production systems or levels of intensification. Different methods in quantifying sustainability has been used, such as life cycle assessment, sets of sustainability indicators, and emergy (with an 'm') synthesis. Additionally, innovative systems, such as integrated multi-trophic aquaculture (IMTA), aquaponics and bioflocs have been developed to achieve higher productivity and sustainability [4–7]. Most of the aquaculture production comes from inland small-scale pond farms in rural areas [3]. Nevertheless, they have received less attention in strategic planning and management within EAA concepts than coastal and marine systems [8,9]. Thus, the EAA framework lacks of a systemic approach for understanding how small-scale freshwater pond aquaculture are connected with the surrounding social, economic and environmental systems.

The small-scale inland pond aquaculture should move towards more sustainable production systems in order to achieve the goals established by EAA guidelines, and by the 2030 Agenda for the Sustainable Development [10]. Strategies towards sustainability includes the use of native species, efficient use of feed and locally available resources, such as water, the level of control and monitoring over the production variables, technical qualification and infrastructure, and residue treatment [2]. Nevertheless, the current strategies are costly and sometimes unattainable by rural small farmers. Moreover, the pandemic, economic crises, and climate change increase the vulnerability of small farms, which demands innovative technologies for adjusting production practices to these challenges and promoting sustainability in the long term.

Brazilian aquaculture achieved economic relevance in the early 1980`s, and currently holds the 8th position in the ranking of major fish producers, with >600 thousand tonnes produced in 2018 [3,11]. Lambari (Characidae) is an indigenous fish group commercialized as live-bait, which culture is growing very fast in Brazil. Production attained ~1000 t, and lambari farms ranked at 5th in number of aquaculture properties in 2019 [11]. Lambari culture is comparable to the most kinds of small-scale land-based fish culture in Brazil. Thus, its technical advantages and disadvantages may be an archetype of similar fish culture farms. Lambari is a group of native low-trophic level freshwater fish species widely distributed in South America, which the production was initially performed only to add income for small farmers. Nevertheless, because of the expansion of the live bait market for sport fishing, lambari production has grown during the past decade. Currently, its production occurs primarily in small aquaculture farms, operating in semi-intensive earthen pond

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systems [12], but the market expansion has attracted investors to implement larger farms (>20 ha) that operate under higher demand for infrastructure and energy.

Several different management practices are used in the farming of lambari [12]. Producers settled their management based on other species culture protocols or on their own tests. Inadequate management practices are often observed, since the scientific information and its access are insufficient to address the needs of producers [12]. As a result, most producers face low productivity, inefficient use of natural resources and high generation of wastes. Currently, there is a gradient in technological level of lambari culture, ranging from farms with no technical support and low control of stocking, feeding, survival and water flow, to farms with qualified employees, indoor hatcheries, monitoring equipment and high control of grow and survival. Nevertheless, the technology applied in all farms rarely relies on scientific-based information.

The absence of scientific-based protocols allied to the high variation in culture management make the lambari farming in Brazil a good model to study the sustainability in freshwater pond fish culture. Furthermore, this situation claims for efforts in establishing more efficient and sustainable lambari farm systems. The assessment of the main aspects that drives sustainability would support the development of a scientific-based management towards more sustainable lambari production. Emergy synthesis is a useful tool for assessing bio-economic systems such as aquaculture [13–15]. This method allows the evaluation of the work done by nature, society and economy on a common basis, identifying the main issues in a holistic way [16]. Therefore, this study applies emergy synthesis to assess the sustainability of lambari aquaculture, providing a systemic perspective on the shortcomings of EAA related to the sustainability of small freshwater aquaculture. Additionally, management practices that negatively affect sustainability in semi-intensive pond freshwater systems were identified and more sustainable alternatives were proposed.

2. Materials and Methods

2.1. Data source and description of the studied farms

Nine lambari production farms were studied. They are located in the São Paulo State, Brazil (Figure 1), a subtropical region that concentrates the production of lambari in Brazil. Farms were selected with the assistance of the São Paulo State Rural Technical Assistance Agency. All farms produce the yellowtail lambari (*Astyanax lacustris*, former *A. altiparanae*) in semi-intensive earthen ponds, intensively fed with commercial feed. Lambari farms differ for land and pond sizes, management strategies, and capital for economic investments in infrastructure and equipment. These

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dissimilarities resulted in the following three categories, or levels of control, according to systems technification degree: low control, moderate control, and high control (Table 1). The farms were grouped in these three levels considering the breeding techniques used (natural, semi-natural or controlled), infrastructure and equipment available, control and monitoring of water quality and supplied feed, and survival rates. The selection process was validated by regional experts in lambari production that work in the national rural offices.

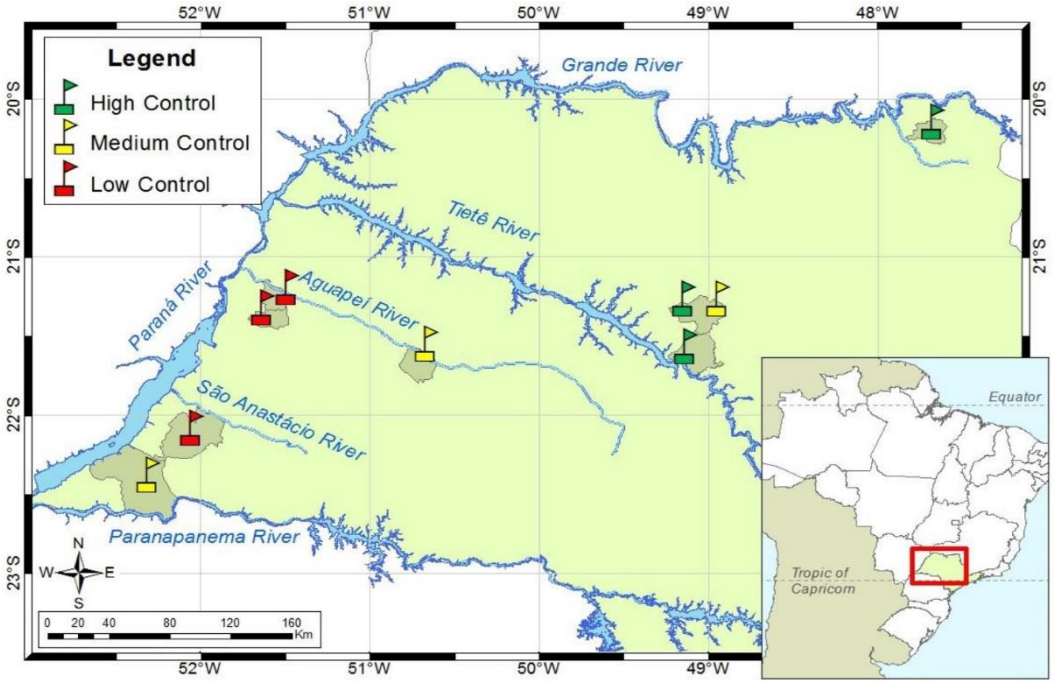

Figure 1. Location of the lambari aquaculture farms studied in the present work. High, medium and low control means a decreasing classification in the level of technification.

Data on natural and economic inputs, management practices and landscape features of each farm were obtained in situ. Samples of water, sediment, diet, and organisms were collected in two visits occurred at the beginning and end of one production cycle in each of the nine farms. Additional information was obtained through a semi-structured survey applied to the nine farmers in the beginning of the production cycle. The questionnaire focused on accounting for the total amount of materials, equipment, and infrastructure purchased, as well as labor, taxes, and depreciation. All inflows of materials, energy and money were accounted in unities/hectare, and they correspond to one year (i.e. 3 production cycles) of farm operation. Farmers validated the data collected at the end of the survey.

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2.2. Emergy synthesis procedure

Data obtained from each farm were subjected to an emergy synthesis. Emergy is all the energy directly and indirectly used to generate a product or a service [16]. This method is a biophysical approach, based on a donor side perspective in establishing value for natural resources, which recognizes all the effort done by nature in making available a resource. Moreover, as a donor side approach, emergy synthesis avoids the inherent subjectivities of the receiver side analysis. The emergy synthesis procedure consists in three main steps: (i) elaborating the energy diagram by defining system's boundaries, input and output flows, and their relationship in internal processes (Figure 2); (ii) quantifying the main flows in the emergy accounting table (i.e. inventory), choosing suitable unit emergy values (UEVs), and calculating the emergy flows; (iii) calculating the emergy indicators to support comparisons and discussions. In the present study, the system boundaries were the same as the farm boundaries, which encompasses the resources that sustain lambari aquaculture and their interactions within the production system. All input resources were categorized as natural renewable resources (R), natural local non-renewable resources (N), or purchased resources from the economy (F). Input resources were accounted in mass (g), energy (J) or money (US$) units, and correspond to one year of farm operation, at one hectare farm basis, allowing for comparisons between farms of different sizes.

Table 1. Characteristics of the evaluated lambari aquaculture systems. Low control (LC), moderate control (MC) and high control (HC) management levels. N/A = not available. Springwater means subterranean water that emerges from the soil reservoirs (aquifers) and is obtained naturally or by pumping.

Production factors	LC	MC	HC
Breeding/spawning	Natural without control	Hormone-induced inside the pond	Hormone-induced controlled hatchery
Production cycle (months)	4	4	4
Crops/year	3	3	3
Total area of ponds (ha)	<1.5	1.5 - 6.2	>6.0
Fertilization regime	Poultry manure	Poultry manure	Poultry manure and/or chemical fertilizer
Stocking seed	larvae	larvae	juvenile
Stocking density - Nursery phase (units/m^2)	N/A	N/A	250
Stocking density - Grow-out phase (units/m^2)	~9	17-25	~30
Pond water exchange (%/day)	3.7	7.0	5.8
Water source	Springwater	Springwater	Superficial water
Diet protein content (%)	28	32-56	32-56
Survival (%)	N/A	N/A	56

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Final fish length (mm)	80.0	93.3	96.6
Final fish mean weight (g)	10	16	18
Productivity (t/ha)	1.8	6.1	6.9

After quantified, the input resource flows were multiplied by their respective unit emergy values (UEVs), resulting in flows of the same unity: solar emjoules (sej). All UEV's used in this work (see Appendix A) were obtained from the scientific literature and the Emergy Evaluation Folios published by the Center of Environmental Policy from the University of Florida. The UEVs were updated to the global baseline of 1.20E+25 sej/yr [17], and do not include labor and services, that were accounted separately as suggested by Ulgiati and Brown (2014). Additionally, the partial renewability values for each resource input were considered when available, as proposed by Agostinho et al. (2018). The sum of the emergy flows in solar emjoules (sej) results on the total emergy demanded (Y). Transformity is the UEV measured in sej/J, which is calculated by dividing the total emergy demanded in sej (input) by the total output measured in joules (output). The emergy indicators calculated in this work are showed in Table 2.

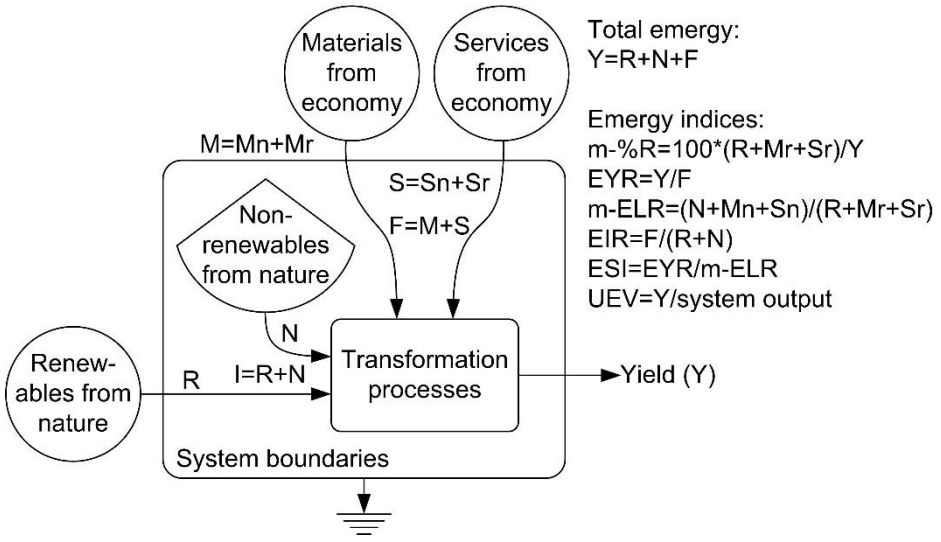

Figure 2. Generic energy diagram with symbols, acronyms and indicators used in emergy synthesis as presented in Table 2. Source: Agostinho et al. (2019). R= renewable resources from nature; r = renewable fraction of a source; N= non-renewable resources from nature; n = non-renewable fraction of a source; I= Inputs from nature; F = resources from the larger economy; M = Materials from economy; S= Services from economy; Y= Yield or total emergy demanded; UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability index.

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Table 2. Emergy indicators used in the present study. R= renewable resources from nature; r = renewable fraction of a source; N= non-renewable resources from nature; n = non-renewable fraction of a source; I= Inputs from nature; F = resources from the larger economy; M = Materials from economy; S= Services from economy; Y= Yield or total emergy demanded; UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability index; sej = solar emjoules.

Emergy indicator	Algebra	Description
Unit emergy value	UEV = Y / E	Ratio of the total emergy demanded by the unity output. Example of units are sej/J, sej/kg and sej/$.
Renewability [a]	m-%R = 100 (R+Mr+Sr) / Y	Ratio of the nature and economy's renewable fraction by the total emergy demanded to produce lambari.
Environmental loading ratio [a]	m-ELR = (N+Mn+Sn) / (R+Mr+Sr)	Ratio of the total non-renewable resources by the total renewable resources.
Emergy yield ratio	EYR = Y / F	Ratio of the total emergy demanded to produce lambari by the resources from economy.
Emergy investment ratio	EIR = F / (R+N)	Ratio of the resources from economy by the nature's renewable and non-renewable resources.
Emergy sustainability index	ESI = EYR / m-ELR	Ratio between the emergy yield ratio by the environmental loading ratio.

Source: Odum (1996)
[a] Indicator modified according to Agostinho et al. (2018).

A resource is defined as renewable when its natural replenishment rate is higher than its extraction rate. In this study, the springwater withdraw rate for LC and MC farm was compared with the natural recharge rate of the regional aquifer, where the farm is located. The natural recharge rate for the regional aquifer is about 25-27% of the yearly rainfall per hectare [20], which is approximately ten times lower than the farms' withdraw rate. Therefore, springwater input was assumed as a non-renewable resource demanded by aquaculture, as similarly considered by similar aquaculture assessments [7,21–23]. The UEV of fish feed was estimated based on a diet formulated for lambari by Sussel et al. (2014) (Appendix B).

2.3. Simulated better scenario

A new scenario was proposed, in which practices that were identified as key factors for decreasing sustainability of the analyzed systems were improved by simulation. Seed production efficiency, water source, fertilization regime and the source of protein and oil used in feed formulation are key variables for conditioning fish productivity. Therefore, they were select to

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project a better scenario for each lambari farm, wherein their effect on the emergy indicators were assessed. This simulated scenario includes the following practices:

Practice 1. Improved seed productivity in LC and MC farms. This practice considers the introduction of substrates inside the ponds used for reproduction in LC and MC farms to protected newly hatched larvae. This is a low-cost technique that reduces larvae losses [25]. Since LC and MC farms have lower control and monitoring of stocking, an increase in seed survival may result in a higher final productivity. Therefore, a 25% increase in productivity for the LC and MC systems was assumed as consequence of adopting this practice. The HC farms perform hormone-induced spawning inside indoor tanks, which allows higher larvae productivity, fish size homogeneity, stocking density control, and survival rate [26]. This efficient and effective practice was maintained in the simulated HC farms. Hormone-induced spawning is expensive and is not affordable for LC and MS farms.

Practice 2. Changing water source in the LC and MC farms. This practice includes the replacement of springwater by superficial water in the LC and MC systems, as currently performed by HC farms. The total water volume used remained the same, and the Unity Emergy Value (UEV) of the water source was replaced (Appendix A).

Practice 3. Controlling pond fertilization in all farms. Fish nutrition is improved by the intake of organisms from the natural biota existing inside ponds. Chemical or organic fertilizers are inputs commonly applied in fish farms, but usually under improperly techniques that leads to inefficiency and wastes generation. To support natural food production, the unruly practices currently performed by farmers were replaced by a controlled fertilization protocol. This practice establishes the use of 0.9 t/ha.yr of lime, 0.56 t/ha.yr of manure, 0.063 t/ha.yr of urea and 0.023 t/ha.yr of phosphorus, and was suggested as a simple and effective protocol for small farms [27].

Practice 4. Replace fish meal protein and fish oil by vegetable protein and oil sources. This practice considers the total replacement of animal protein and oil by vegetable sources in commercial feed, following a diet formulated by Sussel et al. (2014) for lambari. Currently, commercial feed used in lambari aquaculture relies on high protein contents derived from animal sources. Since lambari is a low-trophic level fish, the use of vegetable protein sources rather than animal ones is a feasible alternative that does not affects productivity [24].

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2.4. Result analyzes

Result analyses followed three approaches: (i) emergy index-by-index comparison among the assessed nine-lambari farms considering the current and the simulated scenario practices; (ii) the use of emergy ternary diagram; (iii) emergy sustainability index and global efficiency graph (ESI-UEV).

The ternary diagram is an equilateral triangle, in which the three corners represent each emergy sources (R, N and F). Thus, each system plotted in the diagram is represented by a point, in which R, N and F can be seen by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the vertex of the triangle [14,15]. The emergy ternary diagram is a representation of the emergy performance of each system, allowing a visual comparison among systems in terms of proportion for R, N and F emergy flows [28,29]. Lambari real and simulated data of the nine farms ware plotted in the ternary diagram. In addition, nine other different aquaculture systems, previously studied by other authors, were compared with the present systems.

Sustainability can be measured as an optimum balance between resilience and efficiency [30]. In the ESI-UEV graph, emergy sustainability indicator (ESI) and efficiency (the inverse of UEV) data for each lambari system were plotted on a two-axis graph, in which larger ESI x UEV area represents higher performance. The ESI, accounts for the total environmental pressure of the system over the biosphere capacity (a viewpoint of environmental resilience), and global efficiency (or inverse UEV) measures how efficient a system is for converting the emergy inflow into a product. Therefore, this graph aims to represent which lambari system have the best balance of both.

3. Results

3.1. Lambari production under current practices

The energy system diagram (Figure 3) shows the lambari production features under the systemic view of emergy synthesis. Most of the energy flows comes from outside the farms boundaries, such as sun, rain, commercial feed, equipment, materials and labor. All the lambari aquaculture systems evaluated in this study rely on similar external inputs and internal processes, in which the differences are related to the amount and proportions for R, N and F input resources demanded by each farm. Besides, the high (HC) and moderate (MC) control level systems rely on external labor, either permanent or eventual, while the low control (LC) system relies on local family labor. Energy flows interact within system boundaries with internal stocks of natural capital, hatchery (in the HC farms), and the pond, allowing the production of lambari fish as the main output. Environmental services are co-products and effluents are byproducts produced at different rates

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among farms. Overall, farms with lower control and lower productivity demand lower emergy per hectare compared to the farms with higher control (Table 3). The main inputs for the LC systems are services (27-46%), feed (7-39%) and water (15-21%), while for the MC and HC farms, the main inputs are feed (35-49% and 17-48% respectively) and services (33-39% and 26-36%, respectively). Purchased inputs F were more than 60% of the total emergy required, regardless the level of control (Table 3).

The emergy indicators showed a similar pattern among the evaluated farms regardless the level of control (Tables 4, 5 and 6). The HC1 farm showed the worst performance for UEV, achieving a value approximately 5 times higher than the farm with the best performance (HC2) (Table 6). The HC2 showed the best overall emergy performance among the studied farms, including the highest renewability (m-%R) and sustainability (ESI) and the lowest environmental loading (ELR) and emergy investment ratios (EIR). As well, EIR was slightly lower in the LC farms (Table 4) compared to MCs and HC1 and HC3. Anyhow, all the lambari farms studied are strongly dependent on F resources, which means a low contribution to the larger economy system (EIR > 1), and showed an emergy sustainability index (ESI) bellow 1, which is an indicative of unsustainable systems.

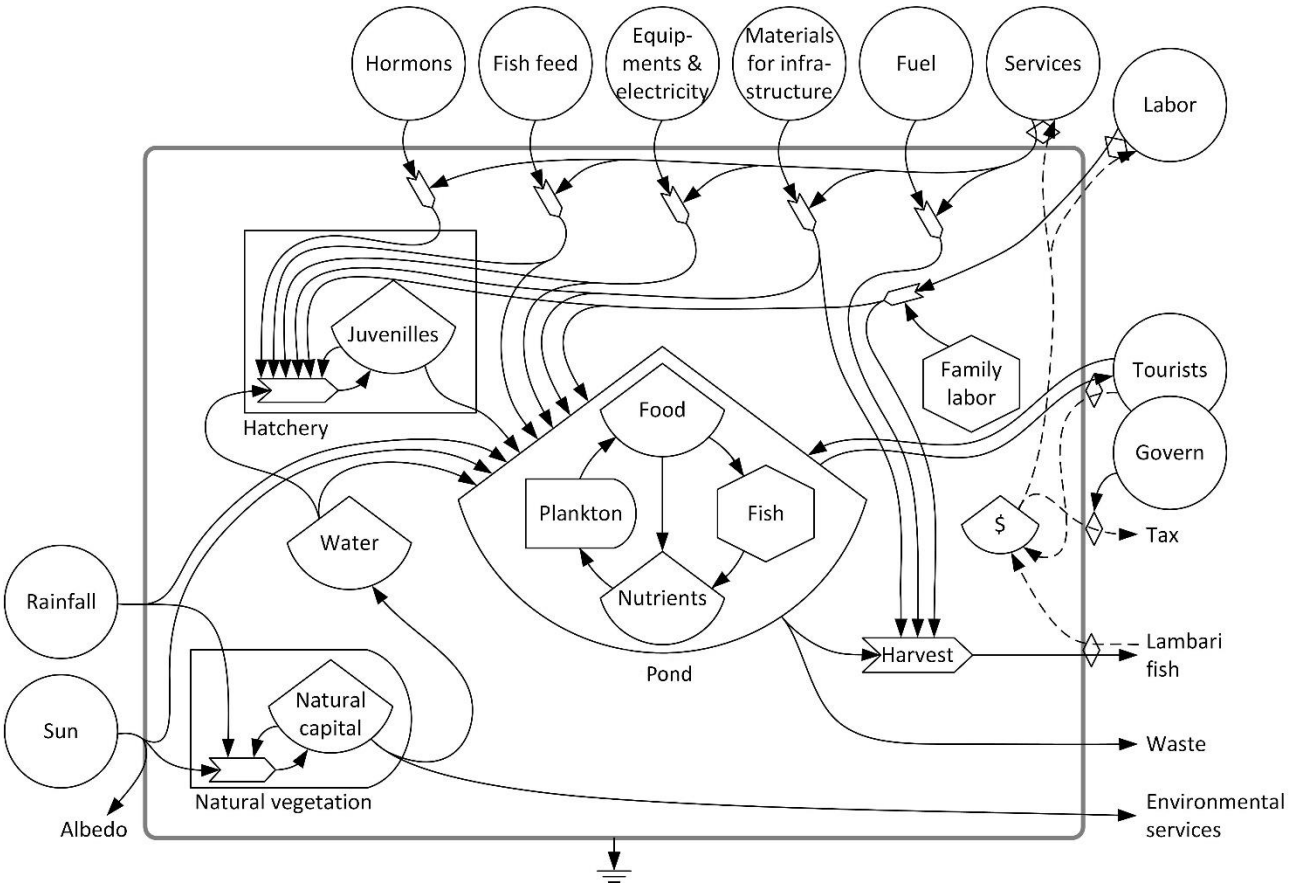

Figure 3. Energy diagram of lambari aquaculture production systems. Hatchery "box" is present only in high control farms (HC). Arrows represent energy flows, circles represents the outside sources,

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stocks are represented by tanks, and energy transformation processes represented by the interaction symbol; dashed arrows represent monetary flows; outputs are the harvested lambari, water effluent and environmental services. Symbol details in Odum (1996).

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Table 3. Emergy accounting results in sej/ha/yr for the nine evaluated lambari aquaculture systems in Brazil. Low control (LC), moderate control (MC) and high control (HC) management levels. Numbers (1, 2 and 3) are the identification of different farms within a same control level. R, renewable resources from nature. N, non-renewable resources from nature. F, resources from the larger economy. Emergy columns presents the emergy flow from each item for each farm. Percentage columns (%) shows the emergy fraction of an item relative to the total emergy (Y) for each farm.

Item	LC1		LC2		LC3		MC1		MC2		MC3		HC1		HC2		HC3	
	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%
Sun (R)	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1
Rainfall (R)	2.12E+15	3	2.12E+15	2	2.12E+15	3	2.12E+15	1	2.12E+15	1	2.12E+15	1	1.36E+15	<1	1.99E+15	2	1.36E+15	1
Superficial water (R)	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.17E+16	3	1.42E+16	17	1.08E+16	4
Soil occupation (N)	1.22E+15	2	8.01E+14	1	3.87E+14	1	3.33E+15	1	1.43E+15	1	2.10E+15	1	2.10E+16	5	3.30E+15	4	1.18E+15	<1
Springwater (N)	1.41E+16	21	2.44E+16	19	1.03E+16	15	1.41E+16	5	1.48E+16	10	1.46E+16	9	0.00E+00	0	0.00E+00	0	0.00E+00	0
Feed (F)	4.77E+15	7	4.95E+16	39	1.87E+16	27	1.26E+17	49	5.43E+16	35	5.89E+16	37	2.19E+17	48	2.63E+16	31	4.02E+16	17
Equipment (F)	1.12E+13	<1	7.27E+14	1	2.13E+13	<1	1.20E+15	<1	1.38E+14	<1	5.25E+14	<1	2.69E+14	<1	1.80E+13	<1	5.89E+15	2
Electricity (F)	9.82E+12	<1	7.24E+14	1	1.92E+13	<1	1.20E+15	<1	1.38E+14	<1	5.21E+14	<1	2.69E+14	<1	1.80E+13	<1	5.89E+15	2
Infra-structure (F)	3.67E+12	<1	5.25E+12	<1	4.09E+12	<1	6.08E+12	<1	2.36E+12	<1	8.52E+12	<1	8.57E+12	<1	1.50E+12	<1	8.73E+12	<1
Lime (F)	4.66E+15	7	4.66E+15	4	4.66E+15	7	4.66E+15	2	4.66E+15	3	4.66E+15	3	4.66E+15	1	4.66E+15	6	4.66E+15	2
Organic fertilizer (F)	9.21E+15	13	9.21E+15	7	9.21E+15	13	9.21E+15	4	9.21E+15	6	9.21E+15	6	9.21E+15	2	9.21E+15	11	9.21E+15	4
Fuel (diesel) (F)	4.98E+14	1	8.62E+14	1	4.88E+14	1	7.32E+15	3	2.36E+15	2	8.79E+15	6	6.10E+15	1	1.46E+15	2	5.58E+16	23
Labor (F)	0.00E+00	0	4.76E+14	<1	0.00E+00	0	6.48E+15	3	5.22E+15	3	6.27E+15	4	1.70E+16	4	1.16E+15	1	2.93E+16	12
Services (F)	3.16E+16	46	3.40E+16	27	2.43E+16	35	8.41E+16	33	6.09E+16	39	5.16E+16	33	1.66E+17	36	2.15E+16	26	8.13E+16	34
Total emergy (Y)	6.83E+16	100	1.27E+17	100	7.02E+16	100	2.59E+17	100	1.55E+17	100	1.59E+17	100	4.57E+17	100	8.38E+16	100	2.40E+17	100
Total (R) [a]	8.25E+15	13	1.18E+16	9	8.23E+15	12	2.44E+16	9	164E+16	11	1.56E+16	10	5.32E+16	12	2.24E+16	27	3.62E+16	15
Total (N)	1.54E+16	23	2.52E+16	20	1.07E+16	15	1.74E+16	7	1.63E+16	10	1.63E+16	11	2.10E+16	5	3.30E+15	4	1.18E+15	<1
Total (F)	4.43E+16	64	8.98E+16	71	1.07E+16	73	2.17E+17	84	1.23E+17	79	1.627E+17	80	3.82E+17	84	5.81E+16	69	2.02E+17	84

[a] Includes the flows of Sun, Rainfall, Superficial water and the renewable fraction from N and F flows.

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Table 4. Emergy indicators for the current management (LC) and the simulated better scenario (LC') of lambari aquaculture low control farms. Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	LC1	LC1'	LC2	LC2'	LC3	LC3'
UEV (E6 sej/J)	2.84	1.86	1.89	1.21	3.07	1.90
UEV (E10 sej/g)	4.88	3.19	4.23	2.72	7.02	4.34
UEV (E6 sej/J)*	1.53	0.79	1.38	0.80	2.01	1.04
UEV (E10 sej/g)*	2.62	1.37	3.09	1.79	4.59	2.37
m-%R (%)	13	37	9	33	12	31
m-ELR	6.9	1.7	9.8	2.0	7.5	2.2
EYR	1.3	1.4	1.3	1.3	1.2	1.3
EIR	3.9	3.4	4.6	4.0	5.5	4.5
ESI	0.2	0.8	0.1	0.7	0.2	0.6

* without services.

Table 5. Emergy indicators for the current management (MC) and the simulated better scenario (MC') of lambari aquaculture moderate control farms. Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	MC1	MC1'	MC2	MC2'	MC3	MC3'
UEV (E6 sej/J)	1.55	1.02	0.91	0.61	2.17	1.44
UEV (E10 sej/g)	3.38	2.23	2.07	1.38	5.09	3.38
UEV (E6 sej/J)*	1.05	0.62	0.55	0.32	1.46	0.32
UEV (E10 sej/g)*	2.28	1.35	1.26	0.18	3.44	0.18
m-%R (%)	9	17	11	23	10	22
m-ELR	9.6	4.8	8.5	3.4	9.2	3.6
EYR	1.1	1.1	1.1	1.2	1.1	1.2
EIR	13.2	11.5	8.4	7.4	8.4	7.4
ESI	0.1	0.2	0.1	0.3	0.1	0.3

* without services.

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Table 6. Emergy indicators for the current management (HC) and the simulated better scenario (HC') of lambari aquaculture high control farms. Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	HC1	HC1'	HC2	HC2'	HC3	HC3'
UEV (E6 sej/J)	4.68	2.54	0.86	0.55	2.47	1.81
UEV (E10 sej/g)	10.3	5.62	2.09	1.33	4.97	3.63
UEV (E6 sej/J)*	2.97	1.45	0.64	0.37	1.63	1.13
UEV (E10 sej/g)*	6.58	3.20	1.56	0.89	3.28	2.27
m-%R (%)	12	14	27	32	15	16
m-ELR	7.6	6.3	2.7	2.1	5.6	5.2
EYR	1.1	1.1	1.3	1.4	1.1	1.1
EIR	13.4	11.4	4.3	3.4	18.0	16.4
ESI	0.1	0.2	0.5	0.7	0.2	0.2

* without services

The ternary diagram (Figure 4a) shows the emergy performance of the nine evaluated lambari farms, compared with nine other aquaculture systems data obtained from literature. All systems are located very close to each other and to the F vertex, indicating a dependence on purchased resources (> 63%), which leads to an overall unsustainable performance (ESI<1).

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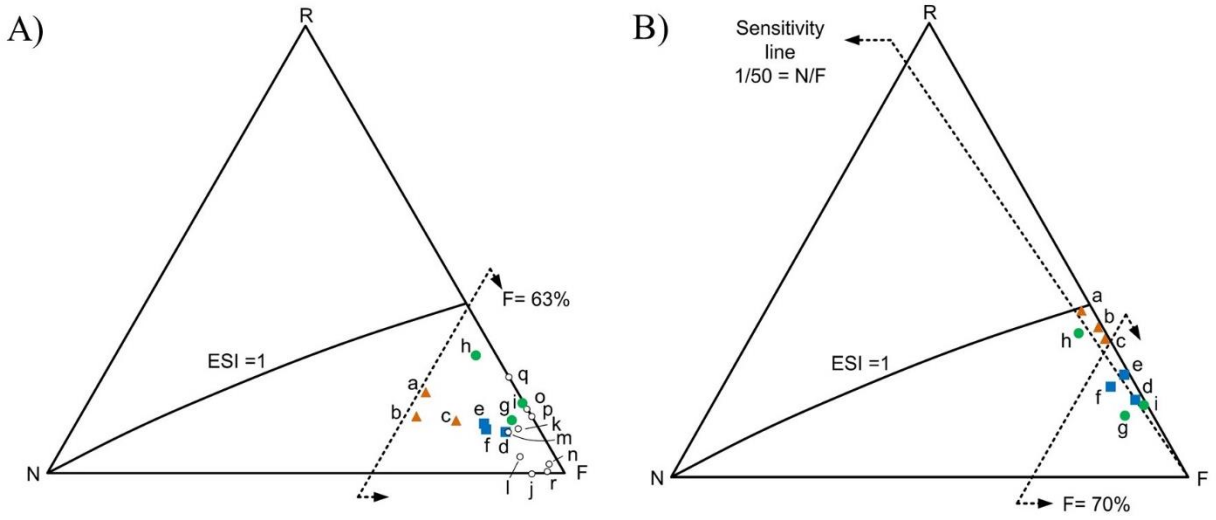

Figure 4. A) Ternary emergy diagram representing the proportions of renewable resources (R), non-renewable resources (N) and resources from economy (F). Evaluated lambari aquaculture systems in the present study were represented by▲, ●, and ■; data from literature were represented by ○. ESI = emergy sustainability index. a = LC1; b = LC2; c = LC2; d = MC1; e = MC2; f = MC3; g = HC1; h = HC2; i = HC3; j = recirculating aquaculture system, k = extensive pond system, and l = semi-extensive system from Wilfart et al. (2013); m = integrated pig-grains-fish culture and n = semi-intensive fish pond system from Cavalett et al. (2006); o = semi-intensive fish pond from Cheng et al. (2017) ; p = net-cage intensive system and q = net-cage intensive system + bamboo substrate from David et al. (2018); r = intensive fish pond from Zhang et al. (2011). B) Ternary diagram representing the proportions of renewable resources (R), non-renewable resources (N) and resources from economy (F) for lambari aquaculture systems after the simulated scenarios for better management practices. Legend: LC systems (▲); MC systems (■); HC systems (●); ESI = emergy sustainability index. A = LC1'; b = LC2'; c = LC3'; d = MC1'; e = MC2'; f = MC3'; g = HC1'; h = HC2'; i = HC3'.

3.2 Simulated better scenario

The simulated scenario led to an improvement of the emergy performance for all evaluated lambari farms, including higher renewability and efficiency, while reducing the environmental loading ratio. The LC systems showed the greatest improvements for renewability (between 164%

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and 255% increase), while reducing the ELRs (between 71% and 80% decrease) and transformities (between 35% and 38% decrease) (Table 4). The MC (Table 5) and HC (Table 6) systems had an increase for renewability (in a range of 81-124% and 6-20% of increase, respectively), and reduced their ELRs (in a range of 50-61% and 7-23% of reduction, respectively) and transformities (in a range of 27-46% of reduction for both systems). Likewise, the ESI of all farms increased. In LC, the ESI increased from 0.2 to 0.7. In MC, the ESI increased from 0.1 to 0.3. In HC, the ESI increased from 0.1 to 0.2 for HC1 and HC3 and from 0.5 to 0.7 for HC2. Although the simulated scenario improved the emergy performance, all the evaluated farms remains below the ESI=1.

Farms LC1', LC2', LC3' and HC2' moved closer to the ESI=1 line compared to their relative position before the simulated scenario (Figure 4), as the proportion of renewable resources was increased. Although increasing their renewability ratios (m-%R), the farms MC1', MC2', MC3', HC1' and HC3' position remain distant from the ESI=1 and close to F vertex, resulted from the high dependence (>70%) on F resources. The sensitivity line indicated that emergy sustainability for the lambari production systems is improved by going in direction of R vertex, but the proportion of 1/50 between N and F resources keeps approximately the same.

The simulated better scenario resulted in higher performance of the ESIxUEV balance (Figure 5) for all the evaluated systems. The LC systems achieved the highest improvement. The system with the higher resilience value, with the larger graphical area for the balance of efficiency and environmental sustainability was the HC2', followed by LC2', MC2', HC2, LC1', LC3', MC1', MC3', MC2, HC3', HC3, HC1', MC1, LC2, LC1, MC3, LC3, HC1 in a hierarchical order.

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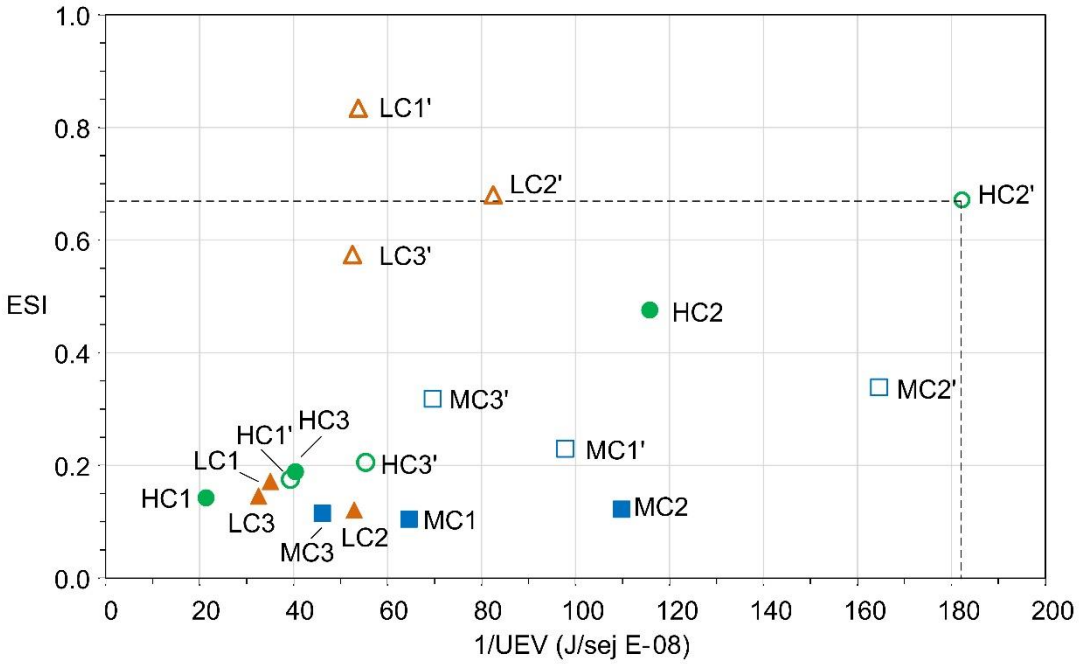

Figure 5. Emergy sustainability index (ESI) and global efficiency (inverse of unit emergy value) for the current management and proposed scenarios for the lambari production farms evaluated. Higher area means higher performance. The dashed line represents the area of the system with higher performance. LC = ▲; LC' = △; MC = ■; MC' = □; HC = ●; HC' = ○. Different colors represent different farms within the same management level: orange = low control; blue = moderate control; green = high control.

4. Discussion

The lambari aquaculture systems evaluated in this study were dependent on similar resources. Despite the existing similarities, farms showed different emergy performances for efficiency, renewability, environmental pressure and nature's investment, regardless of their level of management control. The farms with higher control level (HC) achieved higher productivity. Nevertheless, they are the most dependent on resources from the larger economy (F), making lower use of the local natural resources available. The HC2 farm had the best performance for all emergy indicators, surpassing HC1 and HC3, although they have the same control level. The HC2 consumed less emergy (sej/ha.year) from commercial feed than HC1, and more emergy from organic fertilizers than HC1 and HC3, but reached similar productivity than both. Therefore, HC2 represent a system with more effective use of natural food. Conversely, the LC farms had the lowest productivity and consumed higher volumes of springwater per hectare, which is a local non-renewable resource (N),

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leading to lower emergy performance. These findings indicate that sustainability is not necessarily dependent on the level of control or productivity. Feeding regimes and water management appears as key aspects for the sustainability of lambari production. None farm achieved ESI higher than 1, indicating that all are unsustainable production systems, under the emergy view.

An adequate seed production strategy increases the emergy efficiency of the lambari systems. The strategy adopted by the HC farms demands larger emergy inputs (F), as it requires investments in equipment and infrastructure; moreover, it increases the consumption of electricity and other inputs such as hormones for spawning induction. The high dependence on these F resources decreases systems renewability. On the other hand, this strategy enhances systems productivity, resulting in a larger lambari output that may compensates the expenditures needed by reducing the environmental cost per unity (UEV). Comparatively, HC productivity is ~2.5x higher than LC and ~0.7x higher than MC productivities, considering the currently adopted practices. The simulated scenario of 25% increase in LC and MC productivity, achieved by introducing substrates for improving seed production, enhanced systems efficiency. Substrates can be made from local renewable resources, such as bamboo, which are both environmental and economic low costs. In this scenario, productivity in LC and MC remains lower than HC. Nevertheless, this practice is an alternative for improving the sustainability of lower controlled systems, by increasing their efficiency in the use of natural resources.

Water management makes lower control systems more resilient. Springwater accounts for 15-21% of the emergy input at LC systems, and 5-10% in MC systems. This is a high-quality resource that demands ~10% more emergy than superficial water to be produced and stored by nature [33]. The use of springwater for the grow-out phase of lambari aquaculture is unnecessary, as the aquaculture of lambari can successfully occur with use of nutrient-rich water [34]. The replacement of the water source is a simple strategy that reduces the environmental cost of the lower control systems (Table 3). Moreover, the turnover time of the springwater stock is higher compared to the superficial sources [33]. This fact implies that an overuse makes it a non-renewable resource, which threatens local water security and reduces the resilience of the system. The simulated practice of replacing the water source increased the resilience of LC systems, from an ESI<0.2 at the current scenario to an ESI>0.5 in the simulated scenario. Furthermore, it increased the renewability of LC and MC systems, and reduced the environmental loading ratio in more than 3x for LC and 2x for MC (Tables 4 and 5).

All previous papers on the emergy synthesis of aquaculture considered water as a system input [7,21,23,31,32,35–38]. This study assumed the same approach with the purpose of comparing lambari systems, which are recently studied in the literature, with the related semi-intensive systems.

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Nevertheless, although water is essential for aquaculture, it is a resource “temporarily appropriated” rather than “consumed”, which claims for a different interpretation on how to account for water in aquaculture systems. From the total water used, less than 1% fixes on the fish body, ~10% loses by evaporation and seepage, and the lasting becomes waste [39]. The amount of water embodied by the fish and evaporated or infiltrated should be accounted by its volume (m^3), and considered as R or N, depending on its source. The water that flows through the system and turn into waste, should be accounted by the total emergy needed for recover its original quality, i.e., the emergy of a water treatment system, adequate to the volume and quality of the farm effluent. By this approach, it would be possible to value nature`s investment on recovering a resource that it is damaged by the production system, even though is not been actually depleted. This could model the real environmental cost of water in aquaculture, and guide decision-makers on choices that are more realistic.

A controlled fertilization protocol reduced the environmental cost of fertilizers. The practices currently adopted by lambari producers focus on the use of poultry manure and lime, which comprises a share of 11-20% for LC, 6-9% for MC, and 3-17% for HC, of the total emergy needed. The simulated scenario of a controlled fertilization protocol reduced the emergy of fertilization in ~4x, turning it into a share of less than 6% of the total emergy for all farms studied. Organic fertilizers are co-products from the animal production industry, considered partially-renewable as they are purchased from other production systems (F). The emergy theory sets that co-products of a process have the total emergy assigned to each pathway [40]. In other words, the UEV of poultry manure is the same of the whole poultry production system, since it derives from the same pathways. On the other hand, the use of manure as fertilizers is an open-loop recycling process, in which only the emergy assigned to the post-production processes, such as treatment and deliver, should be accounted at the emergy table [41]. Moreover, if producers could make use of in-site available manure, as in an integrated production system, it would characterize a closed-loop recycling process in which the environmental coast of manure would be zero [41]. These adaptations in the emergy algebra remains under debate within the research community. Nevertheless, results points that although manure is a waste recycled by pond systems, their environmental cost should not be neglected. Therefore, locally available sources should be prioritized, and a controlled fertilization protocol is necessary for reducing costs of natural food production.

Commercial feed is the highest emergy input in lambari farms, as in other fish production systems [7,23,32,42]. It also represents a large share of the emergy on the services input, due to its high monetary cost. The replacement of fish meal and oil by vegetal protein sources is highlighted as a more sustainable alternative for the culture of omnivorous species like lambari, with no decrease in

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productivity [24]. According to the simulated scenario, this practice reduced the emergy of feed by 27%, and increased renewability from 5% to 8%. This practice increased the sustainability more evidently at the higher control farms, as they are higher dependent on commercial feed compared to LC farms. Even though vegetable protein sources are often environmentally cheaper than animal sources, there are aspects of the commercial feed industry that raises controversies under the emergy view. The high industrialization level of the production systems of the crops used in feed composition, by the use of agrochemicals, machinery and long distance transportations, turn them into low or no-renewable sources that demands high emergy to be produced. For example, the UEV of rice bran, and soybean and cottonseed meals can be higher than the UEV of fish meal derived from marine fishery (Appendix B). Furthermore, the use of co-products (or wastes) from the animal production industry, such as bones and viscera, should be accounted properly as described for the case of organic fertilizers. Therefore, from a donor-side perspective, besides prioritizing vegetal protein sources, the use of locally available resources and the recycling of wastes would further increase the sustainability of commercial feed and consequently improve the sustainability of aquaculture systems.

The need for more sustainable production systems is a well-established concern globally. The best method for quantifying such a complex concept in aquaculture has been discussed by many research groups [6,43,44]. The challenge is how to fit the societies` aim of constantly increasing of efficiency in productive systems within the physical limits of our planet. The idea of sustainability as a contingent balance of these antagonistic and complementary terms, rather than a linear advance towards a static state of sustainability, seems more effective [30]. The combination of inverse unity emergy value (UEV.-1) and emergy sustainability index (ESI) provide an image of the self-organization processes of the lambari systems towards sustainability. The systems that are high productive are unable to respond to environmental changes and thus, are low resilient. Conversely, extensive systems do not take full advantage of the available free energy, and fail in competition with more developed systems. The HC2 is the most successful farm in balancing resilience and efficiency (Figure 5). Nevertheless, the simulated practices, as proposed in the scenarios, improved the performance of HC2 and all other studied farms. This fact demonstrates how systems evolutionary process is continuous along with the environmental features, indicating that sustainability is context-dependent and requires constant adaptation. Thus, aquaculture technologies designed in an ecosystem-based approach are likely to succeed on the long-term adaptation processes, building more sustainable aquaculture systems.

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5. Conclusions

All lambari production systems studied rely mostly on non-renewable resources, mainly on commercial feed and water, regardless of the control level (low, moderate or high). The emergy performance of all farms were similar, with slight advantage for the high control (HC). The low renewability (m-%R<15%), high environmental load (ELR>5.6) and low emergy yield ratio (EYR<1.3) indicates that the systems are unsustainable (ESI<0.2). Nevertheless, a simulated scenario of practices including water-source change, control of pond fertilization, increase of productivity by breeding management, and the exchange of animal protein and oil sources by vegetal ones, results in higher emergy performance for all farms. Although the emergy sustainability of the proposed scenario is still low (ESI<0.8) due to the high demand for purchased resources (EYR<1.4), their renewability increased (m-%R<33%) along with a reduction of the environmental loading ratio (ELR>1.7), indicating that the proposed practices provide benefits under an emergy perspective. Additionally, the scenario increased systems resilience, expressed by the emergy sustainability index x global efficiency (ESIxUEV) relationship. Efforts are still needed towards more sustainable systems for the lambari aquaculture production, but the findings of this work highlight the main bottlenecks on the sustainability of small-scale inland aquaculture performed in rural areas. This conclusion is strengthened by the use of the emergy synthesis, which is a holistic approach in assessing sustainability that recognizes the effort of nature in providing resources.

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Appendix A. Inventory and unit emergy values (UEV) for the nine evaluated lambari production systems. Legend: Low control (LC), moderate control (MC) and high control (HC) management levels. Numbers (1, 2 and 3) represent different farms within the same control level. R, renewable resources from nature; N, non-renewable resources from nature; F, resources from the larger economy; %R, renewability fraction in %. Calculation details in the Supplementary Material.

Item and its classification	Unit	UEV [a] (sej/Unit)	Reference for UEV	%R	Amount in Unit/ha/yr								
					LC1	LC2	LC3	MC1	MC2	MC3	HC1	HC2	HC3
1. Sun (R)	J	1.00E+00	Odum, 1996	100	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13
2. Rainfall (R)	J	2.31E+04	Odum, 1996	100	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10
3. Superficial water (R)	J	5.23E+04	Comar, 2001	100	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4. Soil occupation (N)	J	9.42E+04	Brandt-Williams, 2002	0	1.30E+10	8.50E+09	8.50E+09	8.50E+09	1.52E+10	1.52E+10	1.52E+10	1.52E+10	1.52E+10
5. Springwater (N)	J	5.63E+04	Buenfil, 2001	0	2.51E+11	4.34E+11	4.34E+11	4.34E+11	2.63E+11	2.63E+11	2.63E+11	2.63E+11	2.63E+11
6. Feed (F)	g	7.01E+09	Appendix B	5	6.80E+05	7.06E+06	7.06E+06	7.06E+06	7.74E+06	7.74E+06	7.74E+06	7.74E+06	7.74E+06
7. Equipment (F)													
7.1 Iron	g	7.63E+10	Buranakarn, 1998	0	3.40E+00	5.88E+00	3.33E+00	2.00E+01	1.61E+00	4.96E+01	8.33E+00	3.75E-01	2.00E+01
7.2 Plastic	g	3.90E+09	Buranakarn, 1998	0	3.82E+00	1.36E+01	6.69E+00	2.21E+01	4.69E+00	5.39E+01	1.73E+01	1.25E+00	1.93E+01
7.3 Steel	g	5.92E+09	Brown and Ulgiati, 2004	0	1.79E+02	4.95E+02	3.02E+02	1.08E+01	5.81E-01	2.67E+01	1.08E+01	1.33E+00	1.08E+01
7.4 Aluminum	g	1.62E+10	Buranakarn, 1998	0	6.80E-03	1.00E-02	6.67E-03	3.30E-01	1.61E-03	8.18E-01	3.30E-01	3.95E-03	3.30E-01
7.5 Glass fiber	g	1.00E+10	Buranakarn, 1998	0	0.00E+00	0.00E+00	0.00E+00	7.00E-01	0.00E+00	1.74E+01	2.33E+00	3.85E-02	7.00E+00
8. Electricity (F)	J	1.11E+05	Giannetti et al., 2015	68	8.82E+07	6.50E+09	1.72E+08	1.08E+10	1.24E+09	4.67E+09	2.41E+09	1.62E+08	5.28E+10
9. Infrastructure (F)													
9.1 Copper	g	7.43E+10	Cohen et al., 2007	0	3.13E-01	5.41E-01	3.07E-01	0.00E+00	1.47E-01	2.72E-01	1.01E+00	7.77E-02	1.06E+00
9.2 Bricks	g	2.79E+09	Buranakarn, 1998	0	1.31E+03	1.87E+03	1.46E+03	2.18E+03	8.41E+02	3.05E+03	3.05E+03	5.37E+02	3.10E+03
10. Lime (F)	g	1.24E+09	Odum, 1996	0	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06
11. Organic fertilizer (F)	g	3.07E+09	Castellini et al., 2006	16	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06
12. Fuel (diesel) (F)	J	1.37E+05	Brown et al., 2011	0	3.63E+09	6.28E+09	6.28E+09	6.28E+09	1.72E+10	1.72E+10	1.72E+10	1.72E+10	1.72E+10
13. Labor (F)	$	3.23E+12	Giannetti et al., 2018	15	0.00E+00	1.48E+02	1.48E+02	1.48E+02	1.62E+03	1.62E+03	1.62E+03	1.62E+03	1.62E+03
14. Services (F)	$	3.23E+12	Giannetti et al., 2018	15	3.40E+03	1.24E+03	1.24E+03	1.24E+03	9.79E+03	9.79E+03	9.79E+03	9.79E+03	9.79E+03

[a] UEVs updated to the 1.20E25 sej/yr emergy baseline without accounting for labor and services.

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Appendix B-1. Unit emergy value (UEV) estimation for lambari commercial feed. The amount of ingredients relate to 1g of commercial feed and based on Sussel et al. (2014). %R = renewability fraction in %.

Item	Unit	UEV[a] sej/Unit	Amount (Unit)	%R	Renewable emergy flow (sej)	Non-renewable emergy flow (sej)	Total emergy (sej)	Reference for UEV
Rice bran	g	9.70E+08	0.09	0	0.00E+00	8.73E+07	8.73E+07	Brown and McClanahan, 1996
Corn bran	g	1.45E+10	0.26	0	0.00E+00	3.77E+09	3.77E+09	Brandt-Williams, 2002
Soybean meal	g	3.35E+09	0.2	30	1.99E+08	4.71E+08	6.70E+08	Takahashi and Ortega, 2010
Cottonseed meal	g	4.01E+09	0.09	17	6.12E+07	3.00E+08	3.61E+08	Takahashi and Ortega, 2010
Wheat bran	g	1.09E+09	0.2	22	4.88E+07	1.69E+08	2.18E+08	Dong et al., 2008
Poultry viscera meal	g	4.05E+09	0.0325	16	2.11E+07	1.11E+08	1.32E+08	Castellini et al., 2006
Meat and bone meal	g	4.64E+10	0.027	0	0.00E+00	1.25E+09	1.25E+09	Brandt-Williams, 2002
Fishmeal	g	3.13E+09	0.0175	50[b]	2.73E+07	2.73E+07	5.47E+07	Brown and Bardi, 2001
Blood meal	g	4.64E+10	0.01	0	0.00E+00	4.64E+08	4.64E+08	Brandt-Williams, 2002
Total					3.57E+08	6.65E+09	7.01E+09	

[a] UEVs updated to the 1.20E25 sej/yr emergy baseline without accounting for labor and services.

[b] The Brazilian sardinella (*Sardinella brasiliensis*) is one of the sardine species used as a protein source ingredient in animal feed composition. FAO suggests that excessive fishing pressure could exacerbate biomass declines and delay or compromise potential natural recoveries (available at: http://firms.fao.org/firms/resource/13329/en). Therefore, we assumed a 50% renewability for the fishmeal flow due to its current overexploitation.

Appendix B-2. Unit emergy value (UEV) estimation for lambari commercial feed considering the replacement of animal protein sources by vegetal sources. The amount of ingredients relate to 1g of commercial feed and based on Sussel et al. (2014). %R = renewability fraction in %.

Item	Unit	UEV[a] sej/Unit	Amount (Unit)	%R	Renewable emergy flow (sej)	Non-renewable emergy flow (sej)	Total emergy (sej)	Reference for UEV
Rice bran	g	9.70E+08	0.08	0	0.00E+00	7.76E+07	7.76E+07	Brown and McClanahan, 1996
Corn bran	g	1.45E+10	0.24	0	0.00E+00	3.46E+09	3.46E+09	Brandt-Williams, 2002
Soybean meal	g	3.35E+09	0.26	30	2.61E+08	6.20E+08	8.81E+08	Takahashi and Ortega, 2010
Cottonseed meal	g	4.01E+09	0.12	17	8.16E+07	4.00E+08	4.81E+08	Takahashi and Ortega, 2010
Wheat bran	g	1.09E+09	0.20	22	4.88E+07	1.69E+08	2.18E+08	Dong et al., 2008
Total					3.92E+08	4.73E+09	5.12E+09	

[a] UEVs updated to the 1.20E25 sej/yr emergy baseline without accounting for labor and services.