UNIVERSIDADE ESTADUAL PAULISTA – UNESP
CENTRO DE AQUICULTURA DA UNESP

Síntese emergética na aquicultura: estratégias para promover a sustentabilidade da tilapicultura em tanque-rede.

Luiz Henrique Castro David

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SUMÁRIO

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RESUMO

O rápido crescimento da aquicultura pode acompanhar muitos problemas econômicos, sociais e ambientais. Nesse sentido, muitos sistemas, modelos e técnicas de produção têm sido criados e utilizados para gerenciar o uso dos recursos, diminuir os impactos negativos e tornar a aquicultura uma atividade mais sustentável. No entanto, não se sabe quais desses métodos é realmente sustentável. Sendo assim, o objetivo desse trabalho foi fazer uma revisão sobre o uso da síntese emergética para mensurar a sustentabilidade na produção aquícola. Além de aplicar este método para identificar as contribuições advindas da natureza e da economia no sistema de produção de tilápias em tanques-rede; e avaliar se o uso do perifíton como alimento complementar e a redução da densidade de estocagem melhoram os indicadores de sustentabilidade deste sistema. Para isso, foram avaliados e comparados um sistema com densidade de estocagem de 80 $kg.m^{-3}$, 100% de alimentação, sem substrato e sem perifíton; um segundo sistema que utilizou a mesma densidade de estocagem de 80$kg.m^{-3}$, 50% de alimentação, com substrato e perifíton; e um terceiro com menor densidade de estocagem (40 $kg.m^{-3}$), 50% de alimentação, com substrato e perifíton. Para avaliação emergética foram calculados a renovabilidade, transformidade, razão de rendimento emergético, razão de investimento emergético, razão de carga ambiental, razão de troca emergética e índice de sustentabilidade emergética. A diminuição da densidade de estocagem de peixes e da quantidade de ração, aliadas ao uso de perifíton, melhoraram todos os indicadores de sustentabilidade avaliados. Apesar dessa melhora, a redução na densidade demonstrou baixa produtividade. O estudo mostra que técnicas que visem aumentar o uso de recursos renováveis e diminuir os da economia devem ser incentivadas na produção de tilápias em tanque-rede, tornando evidente a necessidade de políticas públicas que incentivem o uso de sistemas sustentáveis.

PALAVRAS-CHAVE: emergia, perifíton, densidade, ração, sustentabilidade.

ABSTRACT

The rapid growth of aquaculture may be accompanied by several economic, social and environmental problems. In this sense, many production systems, models and techniques have been created and used to manage the use of resources, reduce negative environmental impacts, thus making aquaculture a more sustainable activity. However, it is not known which production systems and management practices are truly sustainable, even though the development and application of these technologies are fundamental for the sustainability of the activity. Therefore, the objective of this study was to review the emergy synthesis to measure sustainability in aquaculture production. Despite applying the emergy analysis to identify the contributions of nature and economy in a tilapia cage farming and evaluating if the periphyton exploitation as a complementary food source and a way of reducing stocking densities improves the sustainability indicators of this system. For this purpose, a system with a 80 kg m^{-3}, 100% of feed, without substrate and without periphyton was compared with two other systems: one with the same stocking density of 80 kg m^{-3} and 50% of feed with substrate and periphyton and a second one with a lower stocking density (40 kg m^{-3}) and 50% of feed, substrate and periphyton. For the emergy synthesis, the following variables were calculated: renewability, transformity, emergy yield ratio, emergy investment ratio, environmental loading ratio, emergy exchange ratio and emergy sustainability index. Reduced stocking densities and feed supply, together with the use of periphyton, improved all the evaluated sustainability indicators. Despite this improvement, reduced densities did not demonstrate ecosystem efficiency, due to low productivity rates. This study showed that techniques that aim to increase the use of renewable resources and reduce economy ones, must be encouraged in tilapia productions in cages, making the need of public policies evident, which motivate producers that adopt more sustainable production systems.

KEYWORDS: emergy, periphyton, density, feed, sustainability.

CAPÍTULO 1

INTRODUÇÃO GERAL - ARTIGO DE REVISÃO

Manuscrito formatado nas normas da revista *Aquaculture*

Emergy synthesis on aquaculture: a review

Abstract

Many systems, models and production techniques have been created and used to manage the use of resources, reduce negative impacts on environment, and ensure the sustainability of aquaculture. However, it is not known which production systems and management practices are truly sustainable, even though the development and application of these technologies are fundamental for the sustainability of the activity. Thus, the aim of this review was to characterize the emergy synthesis and to discuss the main applications and potentialities of its use in aquaculture systems. The emergy synthesis is a method that considers the contribution of nature in creating of the product and services, excluding the strictly monetary character present in conventional economic evaluations. In aquaculture, emergy assessment has provided information that enables identifying managements to be applied to make productive systems more sustainable and resilient. In addition, this methodology enables discussing public policies for the valuation of natural resources and payment for ecosystem services in aquaculture.

Keywords: sustainability, emergy, fish farming, renewable resources.

1. Introduction

Consumption of aquatic food has increased in recent years, driven by population growth and increased preference for healthy animal protein sources (Moura et al., 2016). However, fisheries continue providing constant amount of fish and have failed in supply the growing human demand. This scenario has resulted in a rapid growth of aquaculture, making this activity the fastest growing agricultural practice in the last decades (FAO, 2016). In addition to this increase, there are many concerns about the future of aquaculture production, especially in regarding to the negative environmental impacts that this activity may cause (Henriksson et al., 2017; Nhu et al., 2016). Depending on the aquaculture system adopted, the cultivation of aquatic organisms can use natural resources irresponsibly and interfere in the maintenance of biodiversity, through eutrophication of water bodies, pollution by drug residues and dissemination of diseases in the natural environment (Asche et al., 2009; Ottinger et al., 2016; Fry et al., 2016). On the other hand, aquaculture can also generate impacts that can positively affect the environment, e.g. ecosystem services promoted by aquaculture (Aubin et al., 2014). Ecosystem services are made available when the productive process is used to improve the ecosystem, for example, the bivalve farming that improve water quality or the application of wetlands for effluent treatment (Travaini-Lima and Sipaúba-Tavares, 2012; McDonough et al., 2014; Lemasson et al., 2017; Han et al., 2017).

The monetary valuation of the impacts generated by aquaculture is included in the concept of externalities (Aubin et al., 2014). Externalities can be defined as the positive or negative effects of a decision on those who have not taken part of the decision. In aquaculture, positive externalities can be considered when people involuntarily benefit of the activity, such by jobs generation and financial market movement (Aubin et al., 2014). Negative externalities include water pollution and loss of biodiversity, for example (Aubin et al., 2014; Walton et al., 2015; Villasante et al., 2015). In this sense, public and private institutions are trying to promote and develop sustainability of aquaculture, ensuring the maximization of positive externalities (Alexander et al., 2016) and reducing the negative impacts of the activity.

Many definitions for sustainability are found in the literature (Glavic and Lukman, 2007; Ahi and Searcy, 2013). For Johnston et al. (2007) and Valenti et al. (2011), the sustainability can be defined as the management of natural, financial, technological and institutional resources, in order to ensure the welfare and supply the needs of present and future generations. Some aquaculture systems, models and production techniques have been created and used to manage the use of resources and reduce negative impacts on the environment (Boyd et al., 2007). However, many of these initiatives are not based on the concept of sustainability, but on the adoption of specific actions to improve the efficiency of the systems and legalize the production models, such as Best Management Practices (BMP). The use of these practices leads aquaculture to sustainability, but both should not be confused. Some BMPs, such as the reduction on the need for water or medicines, cannot make the production sustainable, especially if is necessary a higher input of non-renewable resources to achieve these desirable results (Read and Fernandes, 2003; Valenti et al., 2010).

The application of BMPs in production systems is essential to the aquaculture development, however not yet known which of these practices lead the aquaculture to sustainability (Valenti et al., 2011). This is because sustainability theme in aquaculture is recent and there are few research groups dedicated to applying methods of sustainability analysis in their studies (Hau and Bakshi, 2004; Chen et al., 2017), even though assessment methods are essential to indicate actions that will make aquaculture a sustainable activity (Valenti et al., 2011; Kimpara et al., 2012). The low use of these methods and the disorderly growth of the activity generate many incorrect management and inefficient environmental protection laws, which do not contribute to the effective development of aquaculture (Boyd, 2003).

Studies that measure the sustainability of aquaculture production are essential to generate more efficient and ecological systems and consequently new technologies (Valenti et al., 2010; Garcia and Kimpara, 2012). In this sense, there are methods that can be applied to show the strengths and weaknesses of each system, besides indicating strategies of how to improve them (Fezzardi et al., 2013). Among the methods available, the emergy synthesis (Odum, 1996) stands out to be a flexible and scientifically robust method. This method can be applied in aquaculture to provide concrete information for decision-making and guide the activity to sustainability (Garcia et al., 2014). In this sense, it is necessary to know the overview of applicability of emergy synthesis in aquaculture, to direct future studies and propose practical strategies for the sustainable development of aquaculture. Thus, the aim of this review was to characterize the emergy synthesis and to discuss the main applications and potentialities of its use in aquaculture systems.

2. Emergy synthesis

Emergy synthesis (ES) is a method proposed by Odum (1996) to eliminate conflicts between environmental preservation defenders and economic development proponents. Additionally, it aims to establish a fast and precise methodology able to account the energy from the resources from economy, but also all energy from nature for production of goods and services (Odum, 1996; Brown and Ulgiati, 2016). This excludes strictly financial character present in the economic conventional assessments, where only the costs of inputs, human-labor and the profit to compose product price are considered (Amaral et al., 2016).

The ES is based on thermodynamic theory and allows all the energy used on system to be transformed into a single unit (solar emjoules, sej). Emergy include human labor, the contribution of nature to the formation of resources, the cost of negative externalities caused by productive activity, besides evaluating and including the losses of ecosystem services. This conversion into a single unit enable to sum all the emergy flows in a single result, besides allowing correlations and comparisons with other systems (Odum, 1996; Amaral et al., 2016).

Emergy synthesis is holistic and embracing. This method allows to guide the rational and economic use of natural resources, due to its capacity to consider the environmental, economic, social and institutional dimensions of sustainability (Brown and Ulgiati, 2004; Amaral et al., 2016). The method can be applied in any production system and its results allow to evaluate the renewability, the net emergy, the environmental load and the emergy exchange ratio between the systems (Ortega et al., 2008). In addition, it is considered a flexible approach because allows the insertion of elements of other analyzes, such as the ecological footprint (Zhao et al., 2013) and life cycle analysis (Liang et al., 2016). In this way, ES provides reliable scientific information that assists in decision making.

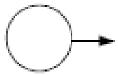
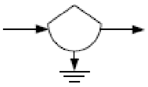
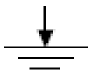
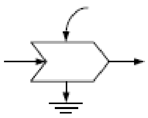
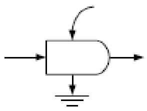
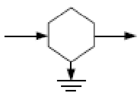
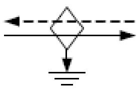
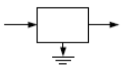
On the other hand, its main limitation is the need for a complex database and difficult to obtain this data. In addition, it requires adequate details about origin of the products and the underlying methods (e.g. financial data), added to this are generalizations and lack of standard in the classification of the inputs of renewable and non-renewable resources, factors that can make the method confusing. Even with these disadvantages, the idea of using emergy to measure sustainability is revolutionary, and is very useful as a scientific method for this purpose (Hau and Bakshi., 2004).

3. Emergy synthesis procedure

Emergy synthesis is based on emergy calculation. Emergy is defined as the energy required directly or indirectly to produce a Joule or kilogram of product or service, expressed in solar emjoules (seJ) (Odum, 1996). To obtain the emergy value of the system it is necessary to know how much energy of each resource enters the process and its respective transformity. Transformity is defined as the rate of emergy required to make a product and its energy, and can be expressed in seJ per Joules, kilograms, or dollars (seJ/J; seJ/g; seJ/US$) (Brown and Ulgiati, 2004). Emergy synthesis was divided into five steps to calculate the amount of emergy entering the production system and to identify the implications of this result (Odum, 1996; Odum, 2000; Brown and Ulgiati, 2004).

The first one (i) is to make an energy system diagram of the process to be analyzed, to identify all the input flows, transformation, feedback, and output of energy. The construction of this diagram should be made using the symbols language (energy systems symbols) to express the direction of the energy flows of the process studied (Table 1). The diagrams show the interactions between natural storages and energy sources that generate new resources, enabling the understanding of system.

Table 1 – Energy systems symbols used in the construction of energy system diagram (Odum, 1996).

Symbols	Description
	Energy circuit: flow of energy, materials or information.
	Source of energy: energy in resources used by the ecosystem (sun, rain, wind, tides).
	Storage: it is the accumulation of a resource, such as biomass, soil, groundwater, nutrients, fossil energy, minerals.
	Heat sink: energy that disperses in a process and cannot be used, such as evaporation of water and heat of metabolism, for example.
	Interaction: A process that combines different types of energies and materials to produce a different resource and perform work.
	Producer: biological autotrophic unit able of transforming solar energy and basic materials into biomass (plants, trees, crops, farms).
	Consumer: biological heterotrophic unit that consumes the resources generated by producers (insects, microorganisms, populations).
	Transaction: exchange of energy, materials, services and money.
	Box: demarcation of limits of a system or subsystem where processes occur.

The second step (ii) is to identify and obtain the values of input flows, used storages and final production. After identification, the inputs should be categorized into: Renewable Resources, Non-Renewable Resources and Resources from economy, the outputs in Yield. Units should be standardized in kg, J, or US$ for time and space (Brown and Ulgiati, 2004). Detailed categorization improves understanding of the process (Table 2).

Table 2 – Detailed classification of inputs and outputs in emergy synthesis.

Inputs and services	Description
I: Inputs of nature resources	I = R + N
R: Renewable resources	Solar energy, rain, wind, materials, and services from preserved areas, nutrients from soil mineral and air.
N: Non-renewable resources	Loss of soil and biodiversity.
F: Feedback of resources from economy	F = M + S
M: Materials	M = Mr + Mn
Mr: Renewable materials	Materials from nature.
Mn: Non-renewable materials	Minerals, chemicals, steel, fuel.
S: Services	S = Sr + Sn
Sr: Renewable services	Human-labor.
Sn: Non-renewable services	Other services (external), taxes, insurance, etc.
Y: Yield	Y = I + F

Note: adapted of Odum (1996) and Lima et al. (2012).

The third step (iii) is to seek for the transformities of the items identified in previous step. These values, in most cases, are available in the literature as results of previous research realized by other authors. If the resource transformity is not found in J or kg units the items can be valued in money unit (US$) and converted into emergy equivalents, multiplying them money by the ratio (ratio = gross national product dollars x emergy from the country in the reference year $^{-1}$) obtained from the national census values (Brown et al., 2000). However, this practice should be avoided to obtain more reliable values and close to the real emergy spend in the process. It is necessary to know the baseline that the Unit Emergy Values (UEV) were calculated, considering that it is determined at different periods and, if necessary, needs to be updated (Campbell et al., 2005; Campbell, 2016; Brown et al., 2016). Differences in baseline are directly related to connectivity between the three primary sources of energy (solar radiation, geothermal sources and tidal impulse dissipation) present in the evaluated processes (Brown et al., 2016). The use of correct baseline allows the comparison of results obtained through different procedures and assumptions.

The fourth step (iv) is the construction of tables to insert the collected data, based on inputs present in diagram created in first step. These tables are constructed in a standard way (Table 3) and assist in the calculation of the system's emergy flow through the introduction of energy input values and their transformities (Brown and Ulgiati, 2004).

Table 3 – Standard table model used to calculate the emergy flows of a system (Odum, 1996; Brown et al., 2000).

1	2	3	4	5	6	7
Note	**Item**	**Unit**	**Energy flow (yearly)**	**UEV* (seJ $unit^{-1}$)**	**Emergy (sej $year^{-1}$)**	**Reference for transformity**
1	Flow 1	J	Value obtained	xxx	xxx	xxx, (xxxx)
2	Flow 2	kg	Value obtained	xxx	xxx	xxx, (xxxx)
n	Flow n	US$	Value obtained	xxx	xxx	xxx, (xxxx)

* Unit Emergy Values (UEV): (1) Transformity (emergy/energy, seJ/J); (2) Specific emergy (emergy/mass, seJ/g); (3) Emergy per unit money (emergy/money, seJ/US$).

The columns in this table can be filled as: (1) Reference note to the item on that line. It should be the same number found in the raw data table where formulas and calculations are listed; (2) Item name, same as used in diagram (e.g. sun, rain, wind); (3) Item unit (J, kg or US$) shown in column 2; (4) Value per time (usually year) of flow (e.g. J/year, kg/year or US$/year); (5) UEV value found in literature (sej/J, sej/kg or sej/US$); (6) Solar emergy flow (column 3 times column 5); (7) Reference of transformity used.

In the fifth (v) and last step, after having all results of emergy flows, it is possible to aggregate them according to their classification and to calculate the emergy performance indicators of system. These were defined and adapted by different authors over time (Odum, 1996; Odum, 2000; Brown et al., 2000; Brown and Ulgiati, 2004), their names and formulas are described in Table 4.

Table 4 – Emergy indices and their equations.

Indicator	Description	Equations*
Tr	Transformity	Tr = Emergy/Energy
%R	Renewability	%R = 100 x (R/Y)
EYR	Emergy yield ratio	EYR = Y / F
EIR	Emergy investment ratio	EIR = F / (R + N)
ELR	Environmental loading ratio	ELR = (F + N) / R
EER	Emergy exchange ratio	EER= Y/ [($) x (sej/$)]
ESI	Environmental sustainability index	ESI = EYR / ELR

*Note: R = renewable resources; N = non-renewable resources; F = resources from economy; and Y = yield.

Transformity indirectly measures the efficiency of the system, this because the ecosystem efficiency of the process or system is established by rate between energy and emergy, the inverse relation of transformity, this means that the greater the transformity, the worse the process's ability to create a service or product (Odum, 1996).

Renewability shows the contribution of renewable resources to the development of system. This indicator ranges from 0 to 100%, higher values mean better performance and lower percentages mean higher environmental stress caused by excessive use of non-renewable resources (Agostinho et al., 2010). In the long term, only processes with higher renewability will support the changes in market, because they do not depend, directly or indirectly, on fossil resources (Brow and Ulgiati, 2004; Ortega et al., 2008).

EYR measures the incorporation of nature's emergy into the productive process. It indicates how much of the primary energy consumed by the product is available for economy. Processes where EYR is 1, or just a little higher, do not provide significant emergy, only transform resources that are already available in others. Primary sources of energy (oil, coal, natural gas) typically show EYRs greater than 5 as they are exploited through a small input of resources from economy and return to much larger emergy flows generated by geological activities over the years. Secondary energy sources and primary materials (such as cement and steel) have EYRs in the range of 2 to 5, indicating a moderate contribution to the economy.

EIR is used to assess whether the economic resource (with monetary cost) will have a good return of natural resources (free) in a project, by measuring the ratio of these two sources. When the contribution from the natural source is high, this ratio is small and costs are low. To be competitive, the process must have EIR value like other productive activities in the region. If the process requires more resources from economy than other options, it will have less chance of sustaining itself.

ELR provides the limit of the carrying capacity of the area where the production process is occurring. The ELR is a measure of the disturbance of local environmental dynamics, generated by the development of human populations. ELR equal to or lower than 2 indicate low environmental impacts or productive processes that use large areas able to dilute the impact. Values between 2 and 10 indicate moderate impacts, while ELR equal to or greater than 10 indicates high environmental impacts, this is due to large non-renewable emergy flows concentrated in a small area.

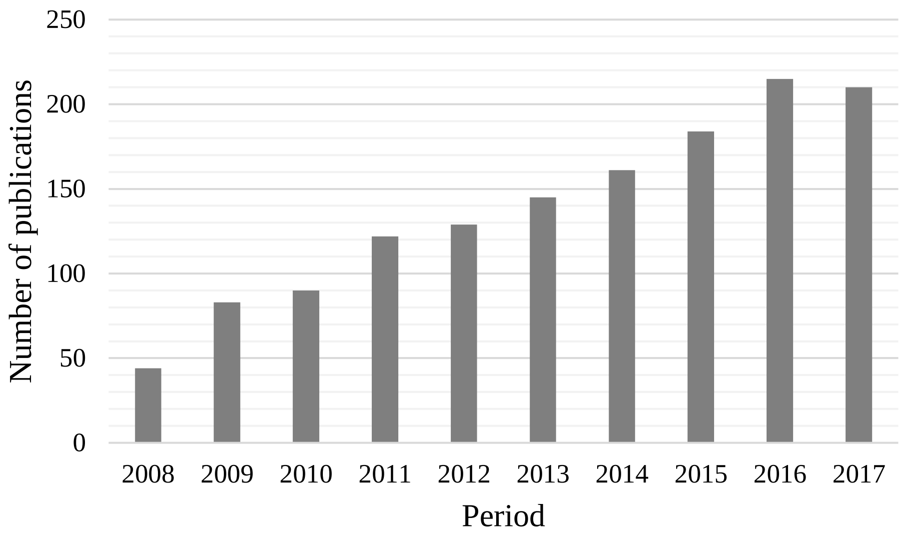
EER is the ratio between the emergy received and provided in a transaction. This indicator evaluated the exchange of resources. Normally industrial nations pay lesser emergy value than the emergy contained in raw materials purchased from underdeveloped countries. Examples of this are minerals, agricultural and fishery products that have a high EER value, however the money received pays only human-labor and does not pay for the environmental service. This situation can be corrected through the application of EER.

ESI measures how much the process contributes to local economy in relation to the environmental load caused and can be considered an indicator of sustainability. According to Brown and Ulgiati (2004) ESI values lower than 1 indicate products or processes that consume emergy, ESI greater than 1 correspond to products that deliver high concentration of emergy to the society and low load do not affect its environmental balance. Regarding the economy of a population, ESI lower than 1 indicates highly developed systems, EIS between 1 and 10 indicate developing economies, while EIS greater than 10 indicate underdeveloped economies.

4. World application of emergy synthesis

Emergy method has been increasingly used to evaluate production systems and ecosystems at different scales. Applications range between evaluating small monocultures (Odum, 2000; Lima et al., 2012), large production systems (Brown and

Ulgiati, 2002; Cheng et al., 2017), ecosystems and local behaviors (Lei et al., 2008; Liu et al., 2009; Pulselli, 2010) or whole countries (Huang, 1998; Brown et al., 2009; Siche et al., 2010). This method is being widely adopted by some groups of scientific researchers (Chen et al., 2016), and it is possible to find an increasing number of papers published with this theme in the last 10 years (2008-2017), searching for the keyword "emergy" in "Science Direct" journal system (Figure 1). Among the themes studied, topics considered as a priority in recent publications of ES are: integrated assessments of human-dominated ecosystems, sustainability assessment, environmental impact assessment and the combination of EA with other methods (Siche et al., 2010; Li and Wang 2009; Chen et al., 2017). The most published journals with this theme are the Journal of Cleaner Production, Ecological Modeling and Agriculture, Ecosystems & Environment.



Source: Science Direct (Elsevier).

Figure 1 - Evolution in the publication of scientific articles and review in the last 10 years with the theme "emergy".

5. Application of emergy method in aquaculture

The use of emergy synthesis in aquaculture has become more popular recently (Zhang et al., 2011). In a search carried out in periodic portals for combinations of keywords "emergy" and "aquaculture" 15 publications were found in recent years (2000-2017). The main results and conclusions of these studies are presented in Table 5.

Table 5 - Review of the studies that applied the emergy assessment to measure sustainability of aquaculture production systems, between 2000 and 2017.

Species and production system	**Objectives**	**Main results and conclusions**	**Reference**
Salmon (*Salmo salar*) in pond monoculture.	Evaluated the sustainability of salmon pond monoculture in United States.	Results showed that the value paid for salmon farmed in ponds should be two times higher as the current price if the environmental resources were valued. Ecosystem performance of salmon production showed that more emergy was needed for this farming than for production of most cultured fish species.	Odum (2000)
Grains, pig and fish in integrated production system and in subsystems in separated way.	Evaluated environmental aspects of integrated production systems of grains, pig and fish in small farms at the South region of Brazil.	Integrated system had better emergy efficiency, was more sustainable and less stressful to the environment compared to grain, pigs and fish production subsystems in a separated way. In this way, the use of integrated systems was encouraged by the authors, because the transfer of emergy between the cultures can be an important strategy to sustainable production.	Cavalett et al. (2006)
Gilthead Sea Bream (*Sparus aurata*) in an inshore fish farming system.	Evaluated the environmental sustainability of an inshore fish farming system in Italy.	The inshore fish farming in a protected area of Mediterranean Sea caused high environmental stress. The largest inputs of emergy were the purchase of fingerlings, goods and services provided. These last two were the main inputs of non-renewable resources into the system. The high dependence on resources from economy and the	Vassallo et al. (2007)

		inability to exploit local natural resources affected the sustainability of this productive process.	
Gilthead Sea Bream (*Sparus aurata*) in an inshore fish farming system.	Verified if a dynamic emergy approach can be used to improve the management of a fish farm by assessing the variations of emergy and transformities during the rearing process. Also, detected the phases of the process that most affect the emergy value of a fish reared in the examined system structure.	The results showed that the patterns of emergy use oscillated during a year due to variations in the climate, the availability of renewable resources and the price of inputs. Among the considered flows, the purchase of fingerlings represented the largest emergy contribution. Thus, to improve the sustainability of the analyzed system, authors suggested that productive schedules should be adopted to improve the efficiency of process, according to seasonal availability of resources and local climatic conditions.	Vassallo et al. (2009)
Monoculture of eel (*Anguilla japonicus*), weever (*Micropterus salmoides),* and polyculture of ophicephalus (*Channa argus*) and mullet (*Mugil cephalus*) in ponds.	Evaluated the sustainability of three production systems through emergy and economic assessment, in China.	The three studied systems presented similar emergy characteristics, but different economic features. Eel farming proved to be the best option for improving the local economy and did not increase the environmental impact. The production of fingerlings in the farm was the strategy found in all cultures to reduce the cost of production and the high input of resources from economy. The study showed that the presence of natural reserves could increase regional sustainability, although these reserves was not economically viable. The authors emphasized that the emergy assessment proved to be a good complement to economic assessment in the evaluation of the production efficiency, environmental	Li et al. (2011)

		impacts, economic benefits, ecological and the sustainability of aquaculture systems.	
Polyculture of grass carp (*Ctenopharyngodon idellus*) and silver carp *(Hypophthalmichthys molitrix*) in cages, reared with natural feeding with plankton; Polyculture of grass carp, silver carp and spotted silver carp *(Aristichthys mobilis)* in ponds, reared with artificial feeding by commercial food; Polyculture of grass carp and silver carp in extensive ponds, reared with artificial feeding by grass gathered around.	Compared the different fish farming systems in relation to resource use and environmental impacts, in China.	Results showed that the main difference between the three production systems was the emergy cost associated with the feed adopted for the fish. The emergy indicators showed that the intensive production with commercial feed was not sustainable. The most intensive management system was characterized by an ESI (emergy sustainability index) less than 0.4, while the other systems showed higher sustainable values. However, the use of plankton and grass was not economically viable.	Zhang et al. (2011)

Extensive polyculture of grass carp (*Ctenopharyngodon idellus*) and silver carp (*Hypophthalmichthys molitrix*).	Evaluated and compared the environmental performance of four local systems of agricultural production: maize planting, duck rearing, mushroom planting and carp polyculture, in China.	Duck rearing and the mushrooms cultivation, activities implemented with the aim of diversifying local agricultural production, were not sustainable. Extensive polyculture of carp presented the best emergy performance, mainly renewability and sustainability indicator.	Zhang et al. (2012)
Conventional semi-intensive and extensive organic shrimp farming (*Litopenaeus vannamei*).	Evaluated and compared the sustainable performance of conventional and organic shrimp farming, in Brazil.	Both systems presented high emergy flow of non-renewable resources. However, the results showed that the indicators of renewability, emergy yield ratio and emergy investment ratio were favorable to the organic shrimp farming. New improvements in the organic system were indicated to increase efficiency and ensure its economic sustainability, given the low price practiced to sale of organic shrimp. The authors suggest that multitrophic systems would be very useful because they allow the increase and diversification of production without increasing the consumption of commercial feed, the main non-renewable source used in aquaculture.	Lima et al. (2012)
Monoculture of kelps (*Laminaria japonica*) and scallops (*Chlamys farreri*), and polyculture of kelps and scallops.	Evaluated the ecological benefits of monoculture of kelps and scallops, and polyculture of kelps and scallops, in China.	Polyculture had the highest sustainability indicator compared to other two isolated monocultures. The study showed that integration was a sustainable aquaculture model.	Shi et al. (2013)

Intensive recirculation salmon (*Salmo salar*) farming; Extensive polyculture of common carp (*Cyprinus carpio*), tench (*Tinca tinca*), roach (*Rutilus rutilus*), perch (*Perca fluviatis*), sander (*Stizostedion lucioperca*) e pike (*Esox lucius*) in ponds; Semi-intensive polyculture of common carp, tench, reach, perch, sander and pike in ponds.	Evaluated the environmental performance of the systems combining the emergy assessment and life cycle analysis, in France.	Recirculation system, with low feed conversion ratio, presented less environmental impact than the two polyculture farms, when the effects on climate change, acidification, electricity demand, soil degradation and water dependence were considered. However, the recirculation system was identified as highly dependent on resources from economy. Polycultures adequately incorporated renewable resources, but had greater environmental impacts due to the inefficient use of economic inputs. This study emphasized that the key factors needed for successful ecological intensification of fish farming should be: minimizing the economic inputs, reducing feed conversion ratio and increasing the use of local renewable resources. The combination of these two methods was a practical strategy to study the optimization of efficiency of aquaculture systems.	Wilfart et al. (2013)
Intensive offshore large yellow croaker *(Pseudosciaena crocea)* farming in cages.	Evaluated sustainability of a small fish farm by using a modified ecological footprint approach based on the ecological footprint method and the Emergy Assessment, in China.	The emergy footprint was 1,953.9 hectares, an area 14 times larger than the support capacity and 293 times larger than the physical area occupied by fish farming. This meant that around 2,000 hectares of ecologically productive land were needed to support the fish farming. The most representative inputs of the emergy footprint were forage, fingerlings and fuel. The authors concluded that the combination of these two assessment methods can serve as a practical and efficient for comparing and	Zhao et al. (2013)

		monitoring the environmental impact of fish farming. In addition, the high dependence on external contributions affected the sustainability of fish farming.	
Tilapia (*Oreochromis niloticus*) cage farming.	Evaluated the sustainability of tilapia cage farming in a hydroelectric reservoir, in Brazil. In addition to simulating management techniques and public policies that contribute to sustainability of this production system.	Emergy assessment showed that the production system is inefficient and pointed out the causes. To solve this problem, it was suggested to adopt managements that proportionally reduce the supply of commercial feed and increase the input of renewable resources. The suggested managements were the reduction in stocking density and the increase in dilution area of the organic load.	Garcia et al. (2014)
Indoor, semi-intensive and extensive farming systems of sea cucumber (*Apostichopus japonicus*).	Evaluated the sustainability and environmental impact of three sea cucumber farming, in China.	Indoor system had greater input and output of resources compared to extensive. The semi-intensive system presented the lowest productivity among the three systems. All emergy indicators of extensive system were better than indoor and semi-intensive system. This indicated that extensive system exerted less stress on environment, used the available resources more efficiently, and better met the requirements of sustainable development compared to indoor and semi-intensive production system.	Wang et al. (2015)
Oyster (*Crassostrea virginica*) aquaculture farm in floating rafts and on-bottom cages.	Evaluated and compared the sustainability of two intensive oyster aquaculture farm, in United States.	Both systems were supported by emergy of resources from economy, such as human-labor, purchase of fingerlings, fuels, goods and services. Compared with other aquaculture products, oyster aquaculture farms were	Williamson et al. (2015)

		supported by a higher percentage of local renewable resources, mainly by particulate organic matter and estuarine water circulation. Overall, the study showed that oyster aquaculture farms generated less environmental impact, greater sustainability and greater benefit to society than other forms of aquaculture. The authors suggested that reducing fuel and electricity use would be two efficient ways to increase the sustainability of oyster aquaculture farm.	
Cropping, poultry rearing, and fish production systems.	Evaluated and compared the environmental performance of three monocultures, in China.	Fish farming had the largest input of renewable resources, showing less dependence on economy compared to other crops. Emergy indicators showed that the fish farming system was more sustainable than other crops. The authors recommended public policies that encourage sustainable agricultural production by local producers, besides the use of clean energy in the productions.	Cheng et al. (2017)

In aquaculture, the ES has been used to evaluate and compare the sustainability of monocultures, integrated production (polyculture), production systems, levels of intensification (intensive, semi-intensive, extensive) and alternatives to traditional managements. These applications were made in productions with different scales, species, locations, levels of intensification, management and structure. These particularities which when transformed in the same unit (solar energy) enabled the comparison between the different scenarios evaluated. In this sense, each situation had its sustainability evaluated within the environmental, economic and social context where it is inserted, in order to present a detailed overview of what is happening and to indicate more efficient solutions regarding the problems found in each locality.

Zhang et al. (2011) showed that the application of emergy synthesis allowed the identification of the emergy of each item or input needed for production, besides verifying where, when and how to modify the different production situations. The results of this method showed which management and actions improve the systems and indicate how they can benefit the environment and local economy (Zhang et al., 2011; Garcia et al., 2014; Williamson et al., 2015). Among all productive items, commercial feed is the main expense emergy of intensive or semi-intensive systems, followed by the purchase of young forms of different species cultivated (Garcia et al., 2014; Cheng et al., 2017). In this sense, management aimed at reducing commercial feed and increasing the use of natural feed is encouraged. In addition, changes in the schedule and production systems, which aim to apply the phase of nursery and growth in the same farm, are also encouraged. This is because both measures have low input of emergy and could increase the renewability of aquaculture production systems (Vassallo et al., 2007).

Overall, the results show that aquaculture production systems cannot be highly productive and at the same time fully sustainable, as they are currently practiced. The productive sector has invested in monoculture intensive systems, to achieve high amounts of fish in small physical spaces and short periods of time (Ayroza et al., 2011), seeking to meet the growing demand for food (FAO, 2016). The consequence is an aquaculture production with high dependence on resources from economy, highly impacting and not sustainable. For example, Vassallo et al. (2007) evaluated the sustainability of intensive cage farming and obtained low values of transformity (Tr) (2.22E+06 sej/J) and emergy sustainability index (ESI) (0.29), and high environmental loading ratio (ELR) (5.00). On the other hand, specific practices in extensive systems have been adopted to seek sustainability and produce food in the most natural way. Zhang et al. (2011) compared levels of intensification of production and found higher sustainability of the extensive system with high ESI (4.61) and low ELR (0.38), compared to semi-intensive (3.98 and 0.55, respectively). The low productivity of the extensive system increased the transformity (5.23E+05 vs. 4.61E+06 sej/J in semi-intensive). In addition, low yields reduce the financial return and makes this system limited to local producers or farms seeking environmental certification to sell their products to a differentiated market.

In the current reality of aquaculture, with scarcity of natural resources and growing pressure for environmentally correct production (Valenti et al., 2011), the trend is the producer seeking systems or managements that corresponds to the market demand, current legislation and the local weather conditions, and the same time use local renewable resources. Vassallo et al. (2007) e Wang et al. (2015) showed that the reduced use of local renewable resources (in relation to the resources from economy) is the main reason to the indicators point the high resources from economy dependence. In fact, when used in massive quantities renewable resources balance the system, making it economically less dependent and more sustainable.

Polycultures or integration of aquaculture with other crops have been presented as promising alternatives to optimize the use of resources by reducing dependence on economic inputs (mainly commercial feed), and increasing productivity (Cavalett et al., 2006; Wilfart et al., 2013; Shi et al., 2013; Cheng et al., 2017). This is because waste generated by one crop serves as input to the other, thus reducing production costs and the emission of pollutants into the environment. The literature also proposes the creation or adaptation of public policies that encourage farmers to adopt sustainable practices on their properties and benefit those already do (Cavalett et al., 2006; Zhang et al., 2012). Regulations for the use of natural resources and support capacity of aquaculture systems are also measures that should be applied (Garcia et al., 2014; Cheng et al., 2017), since all studies (Table 4) that evaluated the emergy exchange ratio (EER) showed that aquaculture products are costing less than they should cost if the environmental value were considered. In this way, these strategies must be adopted to support public policies and generate changes in the aquaculture production chain.

6. Conclusion

The set of information provided by ES supplies technical-scientific subsidies to ensure the planning and adoption of more sustainable production systems in order to ensure the success of long-term activity. The results of using ES to assess aquaculture sustainability indicate the need to increase the use of renewable resources using natural food and integrated production system. In addition, the results of this method allow discussions about public policies for aquaculture and the valuation of natural resources. These strategies can be part of sustainability guidelines in fish production, because they promote the welfare of the community, the environment and the local economy.

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CAPÍTULO 2

ARTIGO CIENTÍFICO

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Improving the sustainability of tilapia cage farming in Brazil: an emergy approach

Abstract

The accelerated and disorderly expansion of aquaculture can lead to economic, social, and environmental problems. In this sense, it is necessary to prioritize the adoption of practices that aim for sustainable production. The aims of the present study were to identify the contributions from nature and economy in the system of tilapia cage farming. In addition, emergy synthesis was utilized to evaluate whether the use of periphyton as a complementary food and the reduction of storage density improve the sustainability of this production system. Three different production managements were evaluated and compared: using traditional stocking density adopted by farmers (80 kg m^{-3}) with 100% of the daily recommended feed and without substrates for periphyton (TRAD); traditional stocking density (80 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (TDS); lower density (40 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (LDS). We calculated using emergy synthesis the transformity (Tr), renewability (%R), emergy yield ratio (EYR), emergy investment ratio (EIR), emergy loading ratio (ELR), emergy exchange ratio (EER), and emergy sustainability index (ESI) of the distinct production managements. The results showed that tilapia cage farming is highly dependent on resources from economy, and feed is mainly responsible for this. Thus, the decrease in stocking density and feed rate, combined with the use of periphyton, improved all emergy indexes evaluated. This occurred because there was a decrease in the use of resources from economy and increase in the use of renewable natural resources. The study shows, through the emergy calculated indexes, that all production managements evaluated should be encouraged in tilapia cage farming.

Keywords: aquaculture; periphyton; density stocking; commercial feed.

1. Introduction

Population growth and the consequent increased demand for high quality food have contributed to the global expansion of aquaculture in recent years (FAO, 2016). However, the disordered development of this activity may have negative effects on the environment (Bronnmann & Asche, 2017). The intensification of systems based on the high use of non-renewable natural resources, combined with the non-adoption of best management practices to achieve high yields, can adversely affect the environmental balance and compromise the future growth of aquaculture (Boyd, 2003; Valenti et al., 2011).

In Brazil, fish farming is represented mainly by tilapia (*Oreochromis niloticus*) and tambaqui (*Colossoma macropomum*) in semi-intensive systems (IBGE, 2015). However, intensive production of tilapia in cages prevails in São Paulo State, which traditionally employs high stocking densities (> 80 kg m^{-3}) and large amounts of feed to achieve high productivity in small cages (Marengoni, 2006). Sometimes this type of farming has caused undesirable consequences, such as accumulation of nutrients in the sediment (Mallasen et al., 2012), the high cost of inputs for the manufacturing of feed (Ayroza et al., 2011; Garcia et al., 2017), outbreaks of diseases and the consequent use of therapeutic products which can result in residue accumulation in the environment and in the fish (Garcia et al., 2013; Monteiro et al., 2016; Maciel et al., 2017).

Methods for sustainability assessment, such as emergy synthesis, point out that sustainable production systems are those that emit low environmental pollutants, use local renewable resources as the main sources of energy, and have low dependence on non-renewable external resources (Brown & Ulgiati, 1997). In this way, it becomes necessary to guide aquaculture farmers to adopt practices that attend to this concept of sustainability to maximize productive efficiency, but also to reduce losses, costs, and negative environmental impacts, increasing the possibility of success over time (Wilfart et al., 2013). One strategy for this is to reduce dependence on feed (Garcia et al., 2014), for example, by reducing the stocking density (Garcia et al., 2013) and using periphyton as a natural food (Garcia et al., 2016).

The use of periphyton to feed cultured fish combined with a decrease in the stocking density improves the growth performance, decreases the time of rearing, and reduces the feed conversion rate in tilapia cage farming (Garcia et al., 2016). This improvement in performance can also provide satisfactory economic results, such as annual yields of up to 57% and 87% higher profitability than the traditional production system (Garcia et al., 2017). However, technical and economic results are not enough to ensure the sustainability of the system because these evaluations do not consider the inputs of environmental resources by the productive activity (Valenti et al., 2011). The adoption of methods that measure sustainability can be a solution to this problem.

Emergy synthesis is one such methodology able to consider environmental and economic aspects of the production systems (Odum, 1996). This methodology considers all inputs and outputs of natural resources in the system, thus allowing for their quantification and comparison in the same aggregate energy base (joules of solar emergy [seJ]), independent of the strictly monetary perception (Odum, 1996; Brown & Ulgiati, 1997; Copeland et al., 2010). It can be used in the decisions and definition of public policies for the use of natural resources, as reported by Lomas et al. (2008) in the evaluation of preservation policies in Spain, and by Pulselli (2010) in the monitoring of resource use by the communities of Abruzzo, Italy.

Thus, we formulate the hypothesis that reduced densities and the use of periphyton as a natural food can reduce the use of non-renewable resources and promote the sustainability of traditional tilapia cage farming, and that the emergy synthesis is a method that can measure the real efficiency of these strategies. The aim of the present study is to evaluate by emergy synthesis if these strategies improve the sustainability of tilapia cage farming. In addition, we identify the contributions from the nature and the economy of this production system.

2. Material and methods

2.1. Systems description

An analysis was conducted on the use of different densities of stocking and periphyton as complementary food (by the introduction of bamboo substrates in the cages and colonization of these microorganisms at the added surface) in tilapia cage farming at the Nova Avanhandava Reservoir, Tietê River, São Paulo State, Brazil (21°11′27,41″ S, 50°03′00,79″ W). Different production managements were evaluated and compared: using traditional stocking density adopted by farmers (80 kg m^{-3}) with 100% of the daily recommended feed and without substrates for periphyton (TRAD); traditional stocking density (80 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (TDS); lower stocking density (40 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (LDS). The production data used were obtained from Garcia et al. (2016) and the economics data from Garcia et al. (2017) (Table 1), all these data represent real situations of commercial production.

Table 1 – Technical and economic characteristics of systems using periphyton as supplementary feed for tilapia in cages at different stocking densities.

Item	Unit	TRAD	TDS	LDS
Stocking density	kg m^{-3}	80.00	80.00	40.00
Feed	%	100.00	50.00	50.00
Substrates	-	No	Yes	Yes
Total production	kg $cage^{-1}$	411.79	417.84	214.54
Weight gain	kg $fish^{-1}$	0.72	0.65	0.71
Feed conversion ratio	-	1.84	1.29	1.06
Productive cycles	cycles $year^{-1}$	1.80	1.49	1.45
Human labor [a]	hours $cage^{-1}$	24.00	26.40	23.40
Cage capacity	m³	6.00	6.00	6.00

[a] Labor (total hours spent by cage) for each activity to rear tilapia in cages with or without use of substrates.

2.2. Emergy synthesis

Emergy synthesis was used to evaluate the sustainability of the cited production managements. From the knowledge of the energy flow of the production system, the diagram was built based on energy systems symbols (Odum, 1996), which presents the energy transformation ways within the systems, from the primary sources and inputs to the final product (Figure 1).

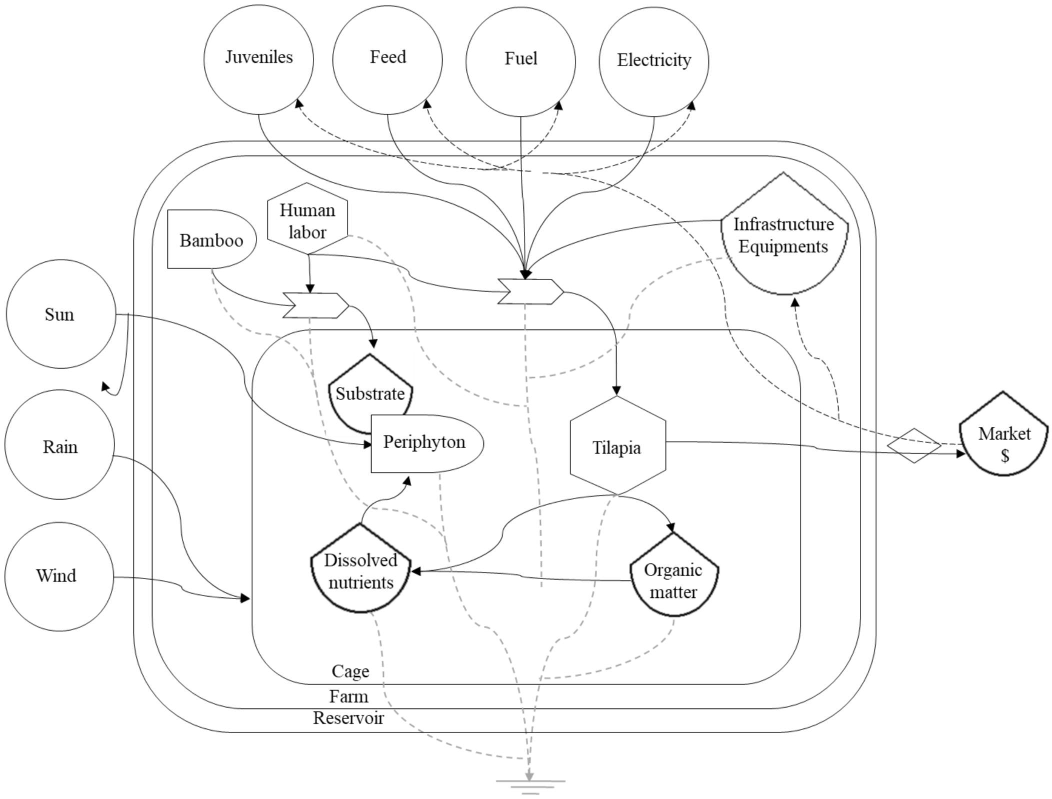

Figure 1 – The energy system diagram of tilapia cage farming with bamboo substrates for periphyton.

Based on the understanding of all energy sources and resources used in the evaluated management, the inputs and outputs of resources were categorized into: renewable resources from nature (R), economic resources (F) as inputs, and yield (Y) as output. The energy inputs were quantified in units of mass (kg) or energy (Joules) to be compatible with the units used in the emergy efficiency factor or transformity of each item. However, some items could not be accounted for in these units and they were valued in monetary unit and converted into emergy equivalents by multiplying the money flow (US$) with the ratio obtained from the national census values (ratio = gross national product dollars x emergy from the country in the reference year $^{-1}$). The equations for the energy calculations of each input are described in the Appendix A. The conversion calculations are described in Appendices B, C, and D.

The inputs of resources had their UEVs (Unit Emergy Value) determined according to the data available in the literature. All the UEVs found are on a baseline of 1.20E+25 sej year^{-1} (Campbell, 2016). When we verified divergences in the baseline, they were converted to obtain updated and comparable values (Campbell et al., 2005; Brown et al., 2016; Brown & Ulgiati, 2016).

For the emergy calculations, the area of one cage (4 m^2 in this study) and the dilution area of the organic load ratio were considered, as established by Brazilian Federal Legislation in 1:8 (BRASIL, 2004). In addition, the legislation of São Paulo State was respected, which establishes a maximum limit of 1% of the surface area of closed or semi-open reservoirs to be occupied by aquaculture parks in state public waters (SÃO PAULO, 2016). Following this, the area of the natural renewable resources supply was defined as 3200 m² per cage.

2.2.1. Emergy indexes

The emergy indices show various aspects of ecosystem, such as resource use intensity, process efficiency, economic-environment interactions, and system's sustainability based on quantitative data of the various emergy flows that are transformed within each tilapia cage farming system analyzed. Thus, the evaluated indices were adapted from Odum (1996) and Brown & Ulgiati (2004) (Table 2).

Table 2 – Emergy indexes used in the evaluation.

Indices		**Formula***
Tr	Transformity	Tr = Emergy/Energy
%R	Renewability	100 x (R / Y)
EYR	Emergy yield ratio	EYR = Y / F
EIR	Emergy investment ratio	EIR = F / (R + N)
ELR	Environmental loading ratio	ELR = (F + N) / R
EER	Emergy exchange ratio	EER= Y/ [($) x (sej/$)]
ESI	Emergy sustainability index	ESI = EYR / ELR

* R: renewable resources from nature; N: non-renewable resources; F: resources from economy; Y: productive yield.

Transformity (Tr) is the ratio between the emergy required to make a product and the energy of it; its unity is the seJ J^{-1} (solar emergy Joule). Renewability (%R) is the ratio of the renewable resources divided by the total emergy of the system. The emergy yield ratio (EYR) is the ratio of the emergy of the product divided by the emergy of the resources from economy used. It provides a measure of how much a production process will contribute to the economy, balancing costs and benefits. The emergy investment ratio (EIR) is the ratio of emergy of resources from economy divided by the emergy of renewable resources from nature. This index shows whether a process efficiently utilizes the emergy that is invested in comparison to other alternatives. The environmental loading ratio (ELR) is the ratio of non-renewable energy, including resources from economy, to renewable emergy. The emergy exchange ratio (EER) is the ratio of the exchange rate to a financial transaction, considering the relation between the emergy contained in the product and the emergy contained in the money received by its sale. These indexes express the exchange ratio of one or more exchange partnerships and is a measure of the relative advantage that is established between the exchange partners. The emergy sustainability index (ESI) is the ratio between the emergy yield ratio (EYR) and the emergy loading ratio (ELR). This is an index that shows the measure of the contribution of a process to the economy per unit of environmental impact that it generates.

3. Results

The production model of 80 kg m^{-3} under traditional management without substrate (TRAD) used 3.78E+15 sej $year^{-1}$ to produce 411.79 kg of Nile tilapia $cage^{-1}$ (Table 3), while the models with food restriction and addition of substrates for periphyton, with 80 and 40 kg m^{-3} (TDS and LDS) required 2.43E+15 sej $year^{-1}$ (Table 4) and 1.46E+15 sej $year^{-1}$ (Table 5) to produce 417.84 kg $cage^{-1}$ and 214.54 kg $cage^{-1}$, respectively. The summarized diagrams, with the emergy flows of each evaluated system, are presented in Figure 2. The resources from economy had the highest proportion of the emergy inputs in all evaluated managements, representing 87% in the TRAD, 78% in the TDS, and 64% in the LDS. On the other hand, the participation of renewable resources from nature was higher in LDS treatment with 36%, compared to 22% in TDS and 13% in TRAD. In the systems with substrate for periphyton, bamboo and periphyton represented approximately 2.5% in both systems (TDS and LDS). The contribution of non-renewable resources from nature was not considered in the three evaluated systems.

Table 3 – Emergy accounting of tilapia cage farming adopting traditional stocking density (80 kg m^{-3}) with 100% of the daily recommended feed and without substrates for periphyton (TRAD).

Note	Item	Unit	Annual flow*	UEV (seJ $unit^{-1}$)	Emergy (sej $year^{-1}$)	Reference
	Renewable resources from nature (Rn)					
1	Sun	J	1.43E+13	1.00E+00	1.43E+13	Odum et al. (2000)
2	Rain	J	2.00E+10	2.36E+04	4.71E+14	Odum et al. (2000)
3	Wind	J	1.32E+09	1.86E+03	2.46E+12	Odum et al. (2000)
	Resources from economy (F)					
4	Juveniles	J	9.04E+08	7.15E+05	6.46E+14	Brown & Bardi (2001)
5	Electricity	J	3.58E+07	8.51E+04	3.05E+12	Häyhä et al. (2011)
6	Gasoline	J	4.61E+07	6.77E+04	3.12E+12	Brown & Bardi (2001)
7	Feed	J	2.56E+10	9.96E+04	2.55E+15	Brown & Bardi (2001)
8	Infrastructure and equipment	$	3.27E+01	2.81E+12	9.19E+13	Coelho et al. (2003)
9	Human labor	J	9.28E+04	9.65E+06	8.96E+11	Brown & Bardi (2001)
	Production yield (Y)					
10	Fish	J	1.35E+10		3.78E+15	

* Values per cage with area for renewable resources of 3.20E+03 m^2.

Table 4 – Emergy accounting of tilapia cage farming adopting traditional stocking density (80 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (TDS).

Note	Item	Unit	Annual flow*	UEV (seJ $unit^{-1}$)	Emergy (sej $year^{-1}$)	Reference
	Renewable resources from nature (Rn)					
1	Sun	J	1.43E+13	1.00E+00	1.43E+13	Odum et al. (2000)
2	Rain	J	2.00E+10	2.36E+04	4.71E+14	Odum et al. (2000)
3	Wind	J	1.32E+09	1.86E+03	2.46E+12	Odum et al. (2000)
4	Periphyton	J	6.31E+09	2.71E+03	1.71E+13	Brown et al. (2006)
5	Bamboo	kg	5.20E+01	4.90E+11	2.55E+13	Liu (2008)
	Resources from economy (F)					
6	Juveniles	J	7.48E+08	7.15E+05	5.35E+14	Brown & Bardi (2001)
7	Electricity	J	8.53E+06	8.51E+04	7.26E+11	Häyhä et al. (2011)
8	Gasoline	J	3.82E+07	6.77E+04	2.58E+12	Brown & Bardi (2001)
9	Feed	J	1.28E+10	9.96E+04	1.27E+15	Brown & Bardi (2001)
10	Infrastructure and equipment	$	3.27E+01	2.81E+12	9.19E+13	Coelho et al. (2003)
11	Human labor	J	7.00E+04	9.65E+06	6.76E+11	Brown & Bardi (2001)
	Production yield (Y)					
12	Fish	J	1.60E+10		2.43E+15	

* Values per cage with area for renewable resources of 3.20E+03 m^2.

Table 5 – Emergy accounting of tilapia cage farming adopting lower stocking density (40 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton (LDS).

Note	Item	Unit	Annual flow*	UEV (seJ $unit^{-1}$)	Emergy (sej $year^{-1}$)	Reference
	Renewable resources from nature (Rn)					
1	Sun	J	1.43E+13	1.00E+00	1.43E+13	Odum et al. (2000)
2	Rain	J	2.00E+10	2.36E+04	4.71E+14	Odum et al. (2000)
3	Wind	J	1.32E+09	1.86E+03	2.46E+12	Odum et al. (2000)
4	Periphyton	J	3.68E+09	2.71E+03	9.95E+12	Brown et al. (2006)
5	Bamboo	kg	5.20E+01	4.90E+11	2.55E+13	Liu (2008)
	Resources from economy (F)					
6	Juveniles	J	3.74E+08	7.15E+05	2.68E+14	Brown & Bardi (2001)
7	Electricity	J	2.88E+07	8.51E+04	2.45E+12	Häyhä et al. (2011)
8	Gasoline	J	3.71E+07	6.77E+04	2.51E+12	Brown & Bardi (2001)
9	Feed	J	5.80E+09	9.96E+04	5.77E+14	Brown & Bardi (2001)
10	Infrastructure and equipment	$	3.27E+01	2.81E+12	9.19E+13	Coelho et al. (2003)
11	Human labor	J	6.04E+04	9.65E+06	5.83E+11	Brown & Bardi (2001)
	Production yield (Y)					
12	Fish	J	3.92E+09		1.46E+15	

* Values per cage with area for renewable resources of 3.20E+03 m^2.

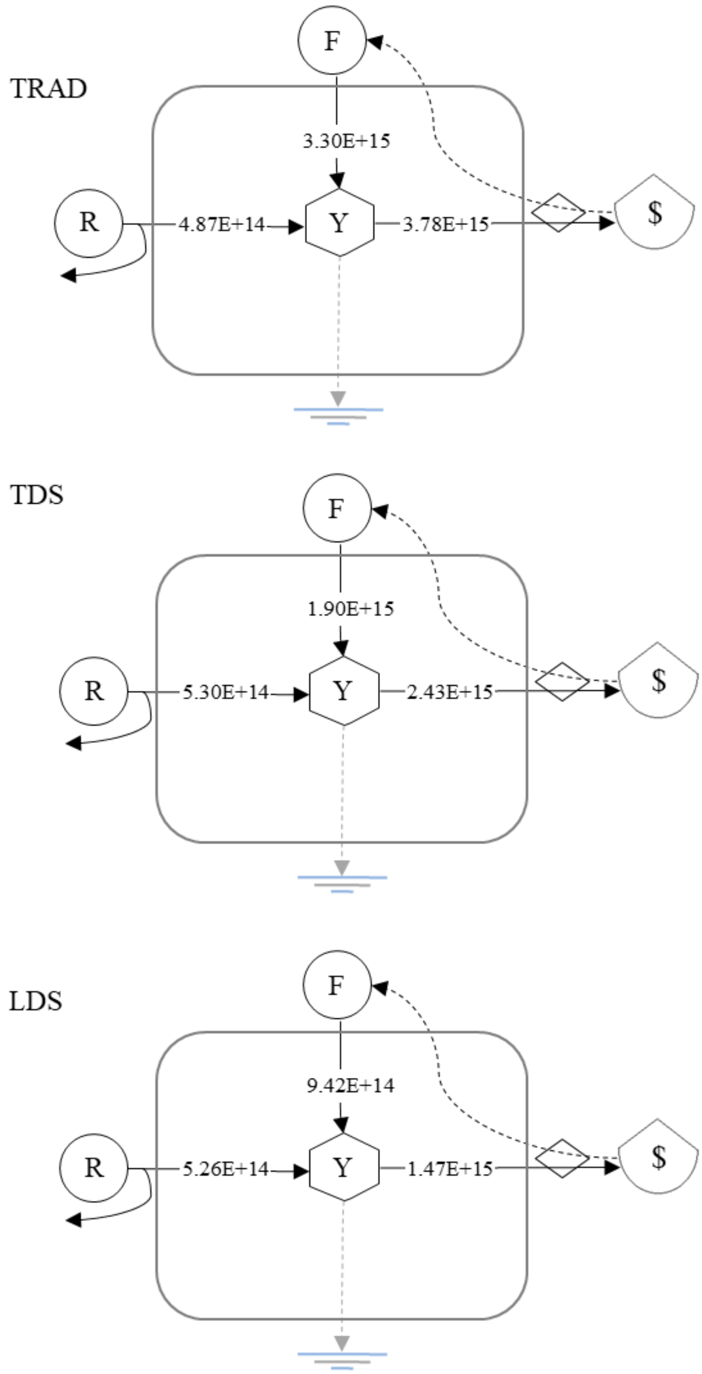

Figure 2 – Summary diagrams of tilapia cage farming emergy flow (sej year^{-1}). R: renewable resources from nature, F: resources from economy, Y: production yield.

In all production managements, the feed was the item with the highest emergy expenditure (Figure 3). In the two treatments that used a density of 80 kg m^{-3} (TRAD and TDS), juveniles were the second most representative item with an average of 19.55%. Meanwhile, in the management that used a density of 40 kg m^{-3} (LDS), the second most representative item was rain, a local renewable resource. Although they have different representability, the amount of renewable resources that entered in the processes were the same in the two strategies, considering that the cages were the same and were in the same place at the same time.

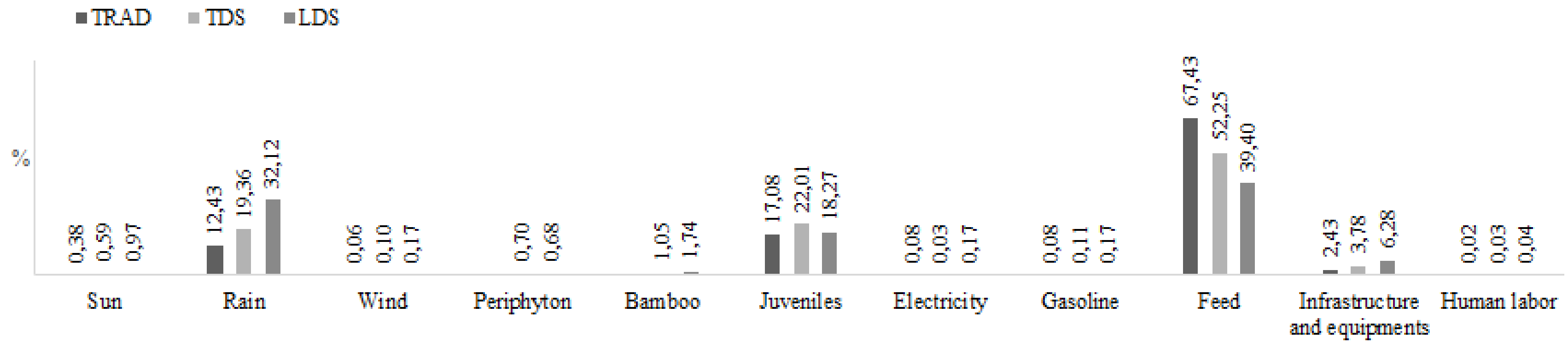

Figure 3 – Representation of energy flows at different situations evaluated. TRAD - Production system using traditional stocking density adopted by farmers (80 kg m^{-3}) with 100% of the daily recommended feed and without substrates for periphyton; TDS - Production system using traditional stocking density (80 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton; LDS - Production system using lower stocking density (40 kg m^{-3}) with 50% of the daily recommended feed and with substrates for periphyton.

The transformity of TRAD was almost twice as high as the TDS (Table 6). However, the LDS presented higher transformity than the other two managements evaluated. The EIR, ELR, and EER indicators had higher values in TRAD, while EYR and ESI were higher in the management that adopted periphyton as a complementary food (Table 6).

Table 6 – Emergy indexes for different situations evaluated.

Indicator	TRAD	TDS	LDS
Tr (seJ/J)	2.80E+05	1.52E+05	3.74E+05
%R	12.87%	21.79%	35.85%
EYR	1.15	1.28	1.56
EIR	6.77	3.59	1.79
ELR	6.77	3.59	1.79
EER	1.18	0.90	1.09
ESI	0.17	0.36	0.87

4. Discussion

In all production managements, the resources from economy were the main items that contributed to the emergy flow (Figure 3). As verified by Garcia et al. (2014), this trend shows that tilapia cage farming is dependent on the economic inputs, and the feed is mainly responsible for this because it has high transformity value and, in intensive aquaculture, is used in large amounts (Ayroza et al., 2011; Garcia et al., 2013; Garcia et al., 2014). The decrease in stocking density and feed amount, when feed restriction and the use of periphyton as complementary food were applied, was not enough to reduce the dependence of resources from economy. However, periphyton and lower stocking density (TDS and LDS) managements used less emergy to produce tilapia in a cage in the one-year period compared to the traditional without substrate for periphyton management (TRAD) (Figure 3). This can be explained by the reduction in the amount of resources from economy with high transformity (such as feed, gasoline, and juveniles) and the inclusion of renewable items with less transformity (such as periphyton, which performs the same function as reduced feed).

Considering that transformity is defined by the inverse relation of ecosystem efficiency, TDS management presented the best result due to the lower value of transformity, which indicates a better process performance to generate a service or product (Odum, 1996; Brown & Ulgiati, 2004) since this management can produce more tilapia by less emergy invested compared to TRAD and LDS. Zhang et al. (2011) discuss this same trend in the evaluation of different aquaculture systems. These authors verified that carp cage farming using natural food achieved better ecosystem efficiency in comparison to the other systems that used commercial feed. In LDS, the lower productivity was responsible for its lower efficiency. Garcia et al. (2014) evaluated different densities and areas for dilution of the environmental load in tilapia cage farming and observed that a lower density negatively affects the efficiency of the system. This trend is evidenced in other studies that evaluated the sustainability of extensive aquaculture systems (Odum, 2001; Bastianoni et al., 2002; Cavalett et al., 2006; Vassallo et al., 2007; Cheng et al., 2017). However, the transformity is an indicator that evaluates only productivity efficiency and does not consider the source of the resource used (e.g., renewable, non-renewable, economic). Because of this, this indicator should not be the only way to evaluate the ecosystem performance (Zhang et al., 2011). In this context, it is necessary to evaluate the other indicators individually and together, since each one has a different approach to analyze the efficiency of the evaluated system.

The renewability (%R) shows that the systems using periphyton (TDS and LDS) are more renewable and less dependent on the resources from economy than the traditional cultivation system (TRAD). This can be explained by the reduction in the use of commercial feed in these treatments, combined with insertion of bamboo substrates for periphyton growth as renewable resources in the system. The high renewability of LDS is a consequence of the combination of these two factors with the use of low density, which reduced the use of resources from economy. This trend also was observed by Garcia et al. (2014) when performing the emergy synthesis of different densities in tilapia cage farming.

In relation to EYR, the values of the three managements can be considered low, reflecting the low contribution of renewable resources revealed in the analysis of the emergy flows. The value of EYR close to 1 in TRAD indicates that the systems were inefficient to incorporate emergy from local renewable resources in the production process (Brown & Ulgiati, 2004). This result also shows that TRAD management make available to society the same amount of emergy consumed in the tilapia production process and did not aggregate emergy to the final product (Li et al., 2011; Cheng et al., 2017). Although the use of periphyton and density reduction (TDS and LDS) increased EYR, values remained low and close to 1, as in other intensive fish production systems evaluated by Cavalett et al. (2006), Zhang et al. (2011), and Vassallo et al. (2007).

The EIR and ELR showed the same performance in all evaluated managements (Table 6); this result is related to the non-inclusion of non-renewable nature items in the emergy synthesis (Odum, 2001). The EIR allows identification of if, in a production process, the use of resources from economy will be equivalent to the natural resources. Quantitatively, this means that lower EIR values indicate a better efficiency in the use of renewable resources from nature, where energy is constantly renewed and can supply the production system continuously (Odum, 1996; Brown & Ulgiati, 2004). In this sense, LDS is shown to have more emergy balance compared to the other treatments. However, in all evaluated managements the input of resources from the economy is much larger than the input of renewable resources. Similar results presented by Odum (2001), Cavalett et al. (2006), and Cheng et al. (2017) suggest that this is probably a standard of aquaculture practice.

On the other hand, the ELR indicates the pressure that the process has on the environment and can be considered a way to measure the environmental stress due to a productive activity. In numbers, ELR values equal to or lower than 2 indicate low environmental impacts, between 3 and 10 indicate moderate environmental impacts, and equal to or greater than 10 indicate high environmental impacts (Brown & Ulgiati, 2004). In this way, the results obtained in the present study (Table 6) show that tilapia cage farming, using periphyton or not, is an activity with moderate impact. Other authors also have classified their aquaculture systems as an activity with moderate impact, independent of the intensification level (Odum, 2001; Bastianoni et al., 2002; Cavalett et al., 2006; Vassallo et al., 2007; Zhang et al., 2011; Cheng et al., 2017). However, the values of the LDS demonstrate that the decrease in stocking density is an efficient alternative to decrease the environmental load generated by the activity. In this management, even with the high input of resources from economy in a small area (4 m^2), the dilution area established by the legislation (3200 m^2) was sufficient to dilute the impacts caused by tilapia culture in this analyzed situation.

Among the evaluated indicators, the EER and ESI give more emphasis to the impact of production on the economy. The EER measures the emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to one or the other trading partner and is a measure of the relative trade advantage of one partner over the other (Brown & Ulgiati, 2004). In a fair trade, the value of EER is equal to 1, indicating the consumer offers emergy in the form of money and receives the same quantity of emergy in the commodity (Zhang et al., 2011). However, in the market as it is practiced today, it is not equitable, since products have much more emergy than what is economically valued (Zhang et al., 2011). The EER aims to correct this imbalance by using the emergy as money, adding the ecosystem value of resources to the value of the product and excluding the strictly economic character, a situation that considers only the value of human labor and the goods of the economy (Odum, 1996; Cavalett et al., 2006).

The EER values of TRAD (1.18) and LDS (1.09) indicate that the production managements analyzed provide more emergy to the consumer than they receive in exchange for their sales. This means that the market underestimates the contribution of nature in the production process. This is a trend of intensive productions that use few resources from nature and has high dependence on the contributions from economy to maintain it (Odum, 2001; Zhang et al., 2011). This same pattern was reported by Cavalett et al. (2006) when analyzing the monoculture of grains, pigs, and fish, and these cultures in an integrated system. The results found by these authors showed that the monoculture of fish, under the conditions analyzed, offers 15 times more emergy to the economy than the value received by sales, and the integrated system offers 6.8 times more. The results obtained by Odum (2001) are similar to those cited. They showed that the sales value of salmon grown in the United States should be double the current if the value of natural resources is incorporated into the production. Therefore, the sale value of tilapia cultivated in a traditional trough (TRAD) or lower density with substrate (LDS) should be higher than that determined by the market. On the other hand, the EER of the TDS was lower than 1 (0.90), showing that if renewable resources started being valued, tilapia cultivated in this way may have its sales value reduced by 10%, making the product cheaper and more accessible to the consumer, as well as stimulating the practice of this production model in relation to the traditional one.

The ESI is an indicator that also considers the economy, measuring how much the production process contributes to the economy in relation to the environmental impact generated–that is, indicates the sustainability of the process (Brown & Ulgiati, 1997; Brown & Ulgiati, 2004; Zhang et al., 2011). Values lower than 1, as found in all the management analyzed in the present study, indicate that tilapia cage farming provides a very low emergy return in relation to the high environmental load they generate. This also seems to be a standard in intensive aquaculture systems, since Odum (2001), Vassallo et al. (2007), and Zhang et al. (2011) recorded this same trend when they used high intensification levels.

In this way, the commercial feed is the main item responsible for making tilapia cage farming in Brazil an activity highly dependent on resources from economy. This large economic participation makes this system very susceptible to market variations, a factor that may make production unviable in possible price variations and the supply of inputs, for example. Studies such as Garcia et al. (2016) and Zhang et al. (2011), which aim to use alternative food to commercial feed, should be encouraged as one of the ways to reduce dependence on the economy and increase the representativeness of nature's renewable resources in aquaculture production. It was verified that management with decrease in density does not seem to be an efficient production strategy (due to the high transformity) but provides the best sustainable performance. According to the emergy analysis, the reduction in artificial feed utilization, as a result of the adoption of substrates with periphyton, should become a practice to be considered in aquaculture because it may possibly facilitate sustainability in the production system.

The results of this study indicate that the adoption of practices and management that reduce the dependence on resources from economy and increase the use of renewable resources help to make aquaculture a resilient and more economically fair activity with lower negative environmental impacts. Moreover, emphasis is placed on the importance of using methodologies that can point out the problems within a production in order to indicate alternative practices aimed at sustainable aquaculture. This information should also be used in the elaboration of public policies that regulate the use of non-renewable resources and the intensification of the aquaculture systems implanted in public reservoirs. The emergy methodology also showed that systems and management based on the premise of increasing aquaculture sustainability must be submitted to these analyses to verify its real development, environmental impact, and ecosystem efficiency.

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Appendix A

Equations for energy calculations of each resource input.

Eq. (A.1) Consumed periphyton (g/year/cage) = (((((feed conversion ratio 1 - feed conversion ratio 2) * final weight of fish)/number of days of the cycle))*number of fish per cage)*365

Eq. (A.2) Solar energy (J) = (area)*(insolation)*(1-albedo)

Eq. (A.3) Rain energy (J) = (area)*(rainfall)*(rain density)*(Gibbs free energy)

Eq. (A.4) Wind energy (J) = (area)*(air density)*(drag coefficient)*(wind velocity^3)*(time)

Eq. (A.5) Periphyton energy (J) = ((protein energy)*(protein concentration in periphyton))+((lipid energy)*(lipid concentration in periphyton))+((carbohydrate energy)*(carbohydrate concentration in periphyton))*(consumed periphyton)

Eq. (A.6) Juveniles energy (J) = (number of fish)*(weight)*(5 kcal/g)*(4186 J/kcal

Eq. (A.7) Electricity energy (J) = (consumption)*(3600000 J/kWh)

Eq. (A.8) Gasoline energy (J) = (consumption)*(10200 kcal/L)*(4186 J/kcal)

Eq. (A.9) Feed energy = ((protein concentration)*(protein energy))+((lipid concentration)*(lipid energy))+(carbohydrate concentration)*(carbohydrate energy))

Eq. (A.10) Total energy feed consumed (J) = (consumed feed)*(feed energy)

Eq. (A.11) Human labor energy (J) = (man-hours)*((2500kcal consumed/number of days per cycle)/24h)*(4186 J/kcal)

Eq. (A.12) Fish energy (J) = ((protein concentration)*(protein energy)*(total production))+((lipid concentration)*(lipid energy)*(total production))+(carbohydrate concentration)*(carbohydrate energy)*(total production))

Appendix B

Table 1 calculations

Note	Item	Value	Unit
1	***Sun***		
	Area	3.20E+03	m²
	Insolation	5.57E+09	J/m²/year
	Albedo	2.00E-01	
	Annual flow	1.43E+13	J/year
	Transformity	1.00E+00	sej/J
	Emergy	1.43E+13	sej/year
2	***Rain***		
	Area	3.20E+03	m²
	Rainfall	1.26E+00	m/year
	Rain density	1.00E+03	kg/m³
	Gibbs free Annual flow	4.94E+03	J/kg
	Annual flow	2.00E+10	J/year
	Transformity	2.36E+04	sej/J
	Emergy	4.71E+14	sej/year
3	***Wind***		
	Area	3.20E+03	m²
	Density of air	1.23E+00	kg/m3
	Drag coefficient	1.00E-03	
	Wind velocity	2.20E+00	m/s
	Annual flow	1.32E+09	J/year
	Transformity	1.86E+03	sej/J
	Emergy	2.46E+12	sej/year
4	***Juveniles***		
	Stocked fish	6.00E+02	unit/year
	Fish weight	4.00E+01	g
	Annual flow	9.04E+08	J/year
	Transformity	7.15E+05	sej/J
	Emergy	6.46E+14	sej/year
5	***Electricity***		
	Consumption	2.86E+00	kWh/year
	Conversion	1.25E+07	J/kWh

	Annual flow	3.58E+07	J/year
	Transformity	8.51E+04	sej/J
	Emergy	3.05E+12	sej/year
6	***Gasoline***		
	Consumption	1.08E+00	L/year
	Annual flow	4.61E+07	J/year
	Transformity	6.77E+04	sej/J
	Emergy	3.12E+12	sej/year
7	***Feed***		
	Consumed feed	1.44E+03	kg/year
	Feed energy	1.78E+07	J/kg
	Annual flow	2.56E+10	J/year
	Transformity	9.96E+04	sej/J
	Emergy	2.55E+15	sej/year
8	***Infrastructure and equipment***		
	Depreciation	3.27E+01	$/year
	Transformity	2.81E+12	sej/$
	Emergy	9.19E+13	sej/year
9	***Human labor***		
	Man-hours	4.32E+01	hours/year
	Annual flow	9.28E+04	J/year
	Transformity	9.65E+06	sej/J
	Emergy	8.96E+11	sej/year
10	***Fish***		
	Total production per cage	7.41E+02	kg/year
	Annual flow	1.35E+10	J/year

Appendix C

Table 2 Calculations

Note	Item	Value	Unit
1	***Sun***		
	Area	3.20E+03	m²
	Insolation	5.57E+09	J/m²/year
	Albedo	2.00E-01	%
	Annual flow	1.43E+13	J/year

	Transformity	1.00E+00	sej/J
	Emergy	1.43E+13	sej/year
2	***Rain***		
	Area	3.20E+03	m²
	Rainfall	1.26E+00	m/year
	Rain density	1.00E+03	kg/m³
	Gibbs free Annual flow	4.94E+03	J/kg
	Annual flow	2.00E+10	J/year
	Transformity	2.36E+04	sej/J
	Emergy	4.71E+14	sej/year
3	***Wind***		
	Area	3.20E+03	m²
	Density of air	1.23E+00	kg/m³
	Drag coefficient	1.00E-03	
	Wind velocity	2.20E+00	m/s
	Annual flow	1.32E+09	J/year
	Transformity	1.86E+03	sej/J
	Emergy	2.46E+12	sej/year
4	***Periphyton***		
	Consumed periphyton	3.94E+05	g/year
	Annual flow	7.35E+09	J/year
	Transformity	2.71E+03	sej/J
	Emergy	1.71E+13	sej/year
5	***Bamboo***		
	Total weight of bamboos	5.20E+01	kg/cage
	Transformity	4.90E+11	sej/kg
	Emergy	2.55E+13	sej/year
6	***Juveniles***		
	Stocked fish	8.94E+02	unit/year
	Fish weight	4.00E+01	g
	Annual flow	7.48E+08	J/year
	Transformity	7.15E+05	sej/J
	Emergy	5.35E+14	sej/year
7	***Electricity***		
	Consumption	2.37E+00	kWh/year
	Conversion	3.60E+06	J/kWh

	Annual flow	8.53E+06	J/year
	Transformity	8.51E+04	sej/J
	Emergy	7.26E+11	sej/year
8	***Gasoline***		
	Consumption	8.94E-01	L/year
	Annual flow	3.82E+07	J/year
	Transformity	6.77E+04	sej/J
	Emergy	2.58E+12	sej/year
9	***Feed***		
	Consumed feed	7.51E+02	kg/year
	Feed energy	1.78E+07	J/kg
	Annual flow	1.28E+10	J/year
	Transformity	9.96E+04	sej/J
	Annual flow	1.27E+15	sej/year
10	***Infrastructure and equipment***		
	Depreciation	3.27E+01	$/year
	Transformity	2.81E+12	sej/$
	Emergy	9.19E+13	sej/year
11	***Human labor***		
	Man-hours	3.93E+01	hours/year
	Annual flow	7.00E+04	J/year
	Transformity	9.65E+06	sej/J
	Emergy	6.76E+11	sej/year
12	***Fish***		
	Total production per cage	6.23E+02	kg/year
	Annual flow	1.60E+10	J/year

Appendix D

Table 3 calculations

Note	Item	Value	Unit
1	***Sun***		
	Area	3.20E+03	m²
	Insolation	5.57E+09	J/m²/year
	Albedo	2.00E-01	%
	Annual flow	1.43E+13	J/year

	Transformity	1.00E+00	sej/J
	Emergy	1.43E+13	sej/year
2	***Rain***		
	Area	3.20E+03	m²
	Rainfall	1.26E+00	m/year
	Rain density	1.00E+03	kg/m³
	Gibbs free Annual flow	4.94E+03	J/kg
	Annual flow	2.00E+10	J/year
	Transformity	2.36E+04	sej/J
	Emergy	4.71E+14	sej/year
3	***Wind***		
	Area	3.20E+03	m²
	Density of air	1.23E+00	kg/m³
	Drag coefficient	1.00E-03	
	Wind velocity	2.20E+00	m/s
	Annual flow	1.32E+09	J/year
	Transformity	1.86E+03	sej/J
	Emergy	2.46E+12	sej/year
4	***Periphyton***		
	Consumed periphyton	1.97E+05	g/year
	Annual flow	3.68E+09	J/year
	Transformity	2.71E+03	sej/J
	Emergy	9.95E+12	sej/year
5	***Bamboo***		
	Total weight of bamboos	5.20E+01	kg/cage
	Transformity	4.90E+11	sej/kg
	Emergy	2.55E+13	sej/year
6	***Juveniles***		
	Stocked fish	3.00E+02	unit/year
	Fish weight	4.00E+01	g
	Annual flow	3.74E+08	J/year
	Transformity	7.15E+05	sej/J
	Emergy	2.68E+14	sej/year
7	***Electricity***		
	Consumption	2.31E+00	kWh/year
	Conversion	1.25E+07	J/kWh

	Annual flow	2.88E+07	J/year
	Transformity	8.51E+04	sej/J
	Emergy	2.45E+12	sej/year
8	***Gasoline***		
	Consumption	8.70E-01	L/year
	Annual flow	3.71E+07	J/year
	Transformity	6.77E+04	sej/J
	Emergy	2.51E+12	sej/year
9	***Feed***		
	Consumed feed	3.28E+02	kg/year
	Feed energy	1.77E+07	J/kg
	Annual flow	5.80E+09	J/year
	Transformity	9.96E+04	sej/J
	Emergy	5.77E+14	sej/year
10	***Infrastructure and equipment***		
	Depreciation	3.27E+01	$/year
	Transformity	2.81E+12	sej/$
	Emergy	9.19E+13	sej/year
11	***Human labor***		
	Man-hours	3.39E+01	hours/year
	Annual flow	6.04E+04	J/year
	Transformity	9.65E+06	sej/J
	Emergy	5.83E+11	sej/year
12	***Fish***		
	Total production per cage	3.11E+02	kg/year
	Annual flow	3.92E+09	J/year

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