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Emergy synthesis for aquaculture: A review on its constraints and potentials

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Abstract

The search for healthier protein sources and the growing demand for food by an increasing world population require aquaculture systems to not only be economically and technologically viable, but also sustainable. Among other methods, emergy synthesis is a powerful tool to assess the sustainability of production systems in a biophysical perspective. However, applications of emergy synthesis on aquaculture systems are seldomly found in the scientific literature. This work provides a literature review on emergy synthesis applied to aquaculture systems and discusses its constraints and potentials. The sixteen papers published between 2000-2020 support the adoption of polycultures more than monocultures and highlight the importance of feed (4–70%) in the total emergy required by aquaculture systems, which require efforts for natural food. Methodological aspects of emergy synthesis applied in aquaculture systems that deserve attention by developers and analysts to avoid mistakes and erroneous conclusions were identified and discussed, and we propose some ways to solve them. These aspects are mainly related to inaccurate unit emergy values for water and feed, dubious procedures in quantifying and classifying water as renewable or non-renewable resources, and the need to recognize the importance in accounting for ecosystem services and disservices. After overcoming these methodological inconsistencies, we foresee that emergy synthesis has potential political implications in supporting most sustainable aquaculture systems through economic (tax reduction and loans with reduced interests) and political (green labels) incentives. All these policies are important to achieve the ultimate goals of the United Nations' Agenda 2030.

Key words: aquaculture production, ecosystem services and disservices, feed, integrated systems, public policies, sustainability assessment.

Introduction

The consumption of aquatic foods has grown in recent years due to population growth and the increase in preference for animal protein from healthy sources (Moura *et al.* 2016). Fisheries have provided a constant amount of fish food in recent years, but they have failed in complying with the growing human demand for this animal protein source. The increased demand for food fish has resulted in an exponential spread of aquaculture production systems, becoming the fastest-growing agricultural practice over the last decades (FAO 2018). At the same time, many concerns are being discussed about the future of aquaculture concerning sustainability, especially because it is highly dependent on non-renewable resources, for example feed (manufactured), electricity, and fossil fuels, and usually releases concentrated waste to the environment (Nhu *et al.* 2016; Henriksson *et al.* 2017). Depending on the technical management adopted, aquaculture might use natural resources over the regional biocapacity and can interfere in the maintenance of biodiversity, since aquaculture production systems can cause eutrophication of water bodies, release drug residues and disseminate diseases in the natural environment (Asche *et al.* 2009; Fry *et al.* 2016; Ottinger *et al.* 2016). These effects are known as negative externalities or ecosystem disservices. On the other hand, aquaculture can also generate benefits or positive effects on the natural environment, which are known as ecosystem services (Aubin *et al.* 2014). An example of an ecosystem service for aquaculture is improving the water quality around oyster farms (McDonough *et al.* 2014; Lemasson *et al.* 2017; Han *et al.* 2017). Evidently, there is a trade-off between economic, social, and natural issues resulting from aquaculture protein production. Aiming to maximize the positive aspects while at the same time reducing the negative ones, public and private institutions are engaged in developing and promoting more sustainable aquaculture production systems (Alexander *et al.* 2016).

In the scientific and technical literature on aquaculture, misunderstandings regarding the concept of sustainability and others, such as best management practices (BMP) and responsible aquaculture (Boyd *et al.* 2007), can be identified. The latter relies on compliance to moral and ethical values of a society, while the BMP focuses on increased efficiency in production systems that may contribute to sustainability, as a secondary goal (Valenti *et al.* 2011). For example, some aquaculture production systems manage the use of resources towards higher efficiency and, therefore, can reduce their negative impacts on the natural environment (Boyd *et al.* 2007). Systems that apply BMPs focus on specific actions to improve their efficiency by reducing the demand for resources such as water and energy, resulting in lower loads in the environment and reduced production costs. While the application of BMPs can be seen as a positive aspect, its concept and goals can only superficially explain the deeper meaning of sustainability. In other words, BMPs in aquaculture should not be considered as synonymous of sustainable aquaculture (Valenti *et al.* 2011). Reducing the use of water, medicines or fossil fuel energy will not make aquaculture sustainable, because a systemic view of production is necessary (Read & Fernandes 2003; Valenti *et al.* 2011).

Considering the business-as-usual approach as supported by the BMPs, allied to faster growth of aquaculture production systems, may lead to technical advancements and environmental protection laws that hardly will contribute to the sustainable development of aquaculture (Boyd 2003). Although seen as essential to generate new technical management that makes production systems (Valenti *et al.* 2018) more efficient and ecological, the theme of sustainability in aquaculture is still recent and there are few research groups studying the application of sustainability assessment methods (Hau & Bakshi 2004; Chen *et al.* 2017). This also explains the reduced number of scientific publications on this subject. There are many methods available that aim to assess the sustainability of production systems in qualitative and/or quantitative aspects, which can be also applied to aquaculture. More than providing a simple diagnosis, most of these methods are important because they provide clear information of actions on the production systems that should be improved to achieve higher degrees of sustainability (Fezzardi *et al.* 2013).

Each method is based on different conceptual models of sustainability, has different windows of interest, concepts, rules, specific accounting meanings and units of measurement (Agostinho *et al.* 2019; Giannetti *et al.* 2019). Among others, the use of Emergy Synthesis (ES) (with an 'm'; Odum 1996) is rapidly increasing to assess the most different production systems, which according to Garcia *et al.* (2014), can shape public policies towards having a sustainable aquaculture. ES is an environmental accounting tool based on the so-called 'strong' conceptual model of sustainability, in which socioeconomic growth is limited by the Earth's biocapacity. ES considers a donor side perspective in providing resources, therefore 'value' is objectively measured in a biophysical approach rather than subjective as in most economic approaches (Odum 1996).

From a systemic perspective and thinking, ES identifies all energy flows supporting a production system, and then quantifies all the effort made by nature in providing these energy flows (Odum 1996; Brown *et al.* 2000). Although respecting the thermodynamic laws regarding energy conservation and entropy, ES recognizes that energy has different 'qualities' according to their position in a hierarchical energy transformation network, which allows it to account for all energy flows from economic and environmental sources to produce goods and services (Odum 1996; Brown & Ulgiati 2016). ES is able to convert all energy input flows into a production system in a single unit of 'solar emjoules' (sej), establishing indicators useful for environmental performance assessment of different production systems (Odum 1996; Ortega *et al.* 2008; Amaral *et al.* 2016). It should be noted that ES requires a vast amount of data that are difficult to obtain and the method occasionally needs to be slightly adapted from case to case. Moreover, ES results are sometimes complex to interpret. Despite these possible disadvantages, all the positive characteristics cited before make ES a powerful tool in assessing sustainability.

ES can be applied to the most different systems, including assessing small monocultures (Odum 2000; Lima *et al.* 2012), large production systems (Brown & Ulgiati 2002; Cheng *et al.* 2017), ecosystems and local behaviours (Lei *et al.* 2008; Liu *et al.* 2008; Pulselli 2010), aquaculture systems (Garcia *et al.* 2014; David *et al.* 2018), or whole countries (Huang 1998; Brown *et al.* 2009; Siche *et al.* 2010). During the last decades, the number of publications in the scientific literature regarding ES increased (Figure 1) due to its strong scientific-based characteristics in quantifying sustainability and supporting decision-makers in having more sustainable production systems. The total number of publications on ES approximately has increased linearly over the past 20 years, while ES for aquaculture shows a low and constant number of publications every year.

Specifically, for aquaculture, the use of ES is relatively new (Figure 1) and is lower in number compared to other multicriteria methods (Garcia *et al*. 2016; Pinho *et al*. 2017; Coutinho *et al*. 2018; Vergara-Solana *et al*. 2019; Battisti *et al*. 2020). Although the growing number of articles that used ES to support discussions and proposals for more sustainable aquaculture production systems is seen as a positive aspect, misunderstandings and/or a lack of clear criteria is generally found in published articles. These problems are found mainly in the use of emergy value units – a conversion factor used in ES – labelling a resource as renewable or non-renewable, and procedures for establishing and evaluating ecosystem services and disservices of specific production systems, among other important aspects that deserve attention so as to improve the method to obtain more sustainable aquaculture production systems.

This review was performed due to the growing demand for more sustainable aquaculture production systems that recognize the Earth's biophysical restrictions in providing resources and diluting residues, and due to the existing scientific robustness of ES as a tool in quantifying this sustainability. This paper aims to provide a review of the most recent and important high-quality published papers on aquaculture systems in order to sustain a discussion on its main outcomes, gaps and patterns, as well as focusing on the application of the ES method to assess their advantages and limitations when evaluating aquaculture systems.

Review methodology

There are four parts in this review paper. The first part is a quantitative summary of what has been studied on ES for aquaculture, including regional distribution, main outcomes, objectives, and specificities of production systems. Secondly, these identified resources as main contributors to the emergy performance of aquaculture systems are discussed in detail to identify improvements in the technical management of these systems. Thirdly, misunderstandings, limitations and potentials are discussed about how to account for key energy inputs when applying ES on aquaculture systems. Fourthly, the importance of ES for the advancement of a sustainable aquaculture is discussed considering what has been done in the field and its importance.

Our review process includes exclusive articles in English published in refereed journals. The Science Direct (sciencedirect.com), Web of Science (webofknowledge.com) and Google Scholar (scholar.google.com) databases

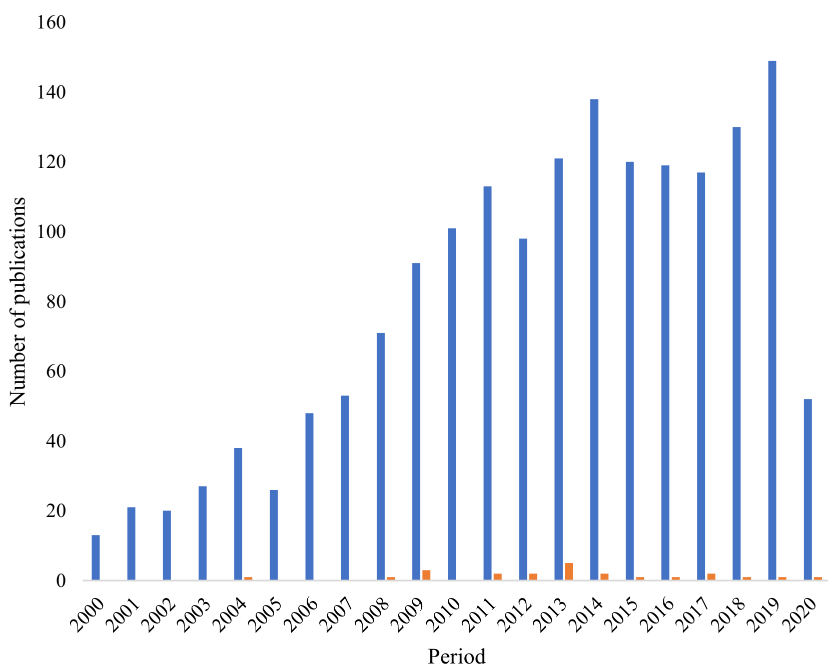

Figure 1 Evolution in the publication of scientific articles and review in the last 20 years with the theme emergy compared to emergy applied for aquaculture. ■, Emergy; ■ Emergy Synthesis for Aquaculture. Sources: The Science Direct, Web of Science and Google Scholar databases.

were used as references to support our review. Papers published until January 2020 were considered and the following terms were set in the fields of titles, abstracts and/or keywords: "emergy synthesis + aquaculture", "emergy + aquaculture", "emergy assessment + aquaculture", "emergy analysis + aquaculture", "emergy accounting + aquaculture", "aquaculture production + emergy", and "fish farming + emergy". Using these terms, the search returned many articles with emergy and/or aquaculture; however, we selected only those that used ES to assess the sustainability of aquaculture systems. The reference lists presented in the articles were cross-referenced in our review; in other words, they were also verified in order to find the articles that were not selected at first. This method of searching and selecting articles was also used to prepare Figure 1.

Overview of emergy synthesis applied to aquaculture systems

Using ES in aquaculture has become more popular recently. According to our review, besides existing work published in 1991, only after 2000 can an increase in published papers be observed, reaching 16 papers until January 2020. In general, ES has been used to assess sustainability of monocultures, integrated production (polyculture), levels of intensification (intensive, semi-intensive, extensive) and alternatives to traditional management. Applications occurred in production systems for different scales, species, regional distribution, levels of intensification, management and structures. Table 1 presents an overview of papers considered in our review work.

In current practice of aquaculture, given the scarcity of natural resources and the growing pressure for environmentally correct production (Valenti *et al.* 2011), the trend is that producers seek systems or management strategies that correspond to the market demand, current legislation, local weather conditions, and at the same time the use of local, renewable resources to increase their sustainability. However, fully sustainable aquaculture production systems are rarely found. Instead, there is a gradient between sustainable and unsustainable systems. According to Zhang *et al.* (2011), different levels of sustainability can be measured, recognized and categorized. From an emergy perspective, aquaculture as it is currently practised is highly dependent on resources from economy and non-renewable natural resources which is an indicative of low sustainability. Therefore, identifying the emergy input flows on a production system that can positively or negatively act on its environmental performance is a crucial step to guide aquaculture for sustainable development. Negative aspects indicate weaknesses in the production process and show the need for improvement. For example, Vassallo *et al.* (2007) and Wang *et al.* (2015) showed that using resources from the economy, for example labour, fuel, capital costs, etc., is a weakness in aquaculture production in the Mediterranean and China, whereas they could be using local renewable resources to replace those economic resources. Using massive quantities of renewable resources balances the system according to the natural capacity of the region in which they are located, making it economically and ecologically stronger and more sustainable (Vassallo *et al.* 2007; Wang *et al.* 2015).

ES applications can identify the emergy flows of each resource that drives aquaculture production, which verifies where, when and, sometimes, how to improve the systems' emergy performance. ES results show which technical managements can lead to environmental improvements, indicating how they can benefit from the environment and the local economy (Zhang *et al.* 2011; Garcia *et al.* 2014; Williamson *et al.* 2015). Analysing the studies presented in Table 1 enabled us to precisely identify some patterns on the representativeness of the emergy flows that affect aquaculture production. Feed and purchase of juveniles or fingerlings are the items identified with the highest emergy expenditure. Another important aspect is related to monocultures, which commonly demand more emergy from non-renewable resources compared to polycultures or integrated cultures, thus reducing their efficiency and sustainability. Considering the papers presented in Table 1, the adopted production technique and high contribution of non-renewable resources on emergy input flows are the main drivers leading aquaculture to unsustainability. Hence, there is a need for more research to assess alternative production systems that reduce their demand for non-renewable emergy, thus respecting their local biocapacity.

Through the review process, another important aspect is related to accounting procedures in emergy as considered by the authors. Inconsistencies were found regarding the choice of the unit emergy value (UEV) for water and feed input flows, and the way in which water resources were labelled as renewable or non-renewable resources. Furthermore, the lack of inclusion of ecosystem services and disservices, items generated during the production process, in the emergy synthesis of aquaculture systems was also identified. Due to their importance in ES, they are all described in detail in the next sections.

Insights into the main issues regarding the emergy synthesis for aquaculture

Aquaculture producers have invested in monoculture, resource-intensive systems to produce large 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 2018) and at the same time aiming for higher profits.

Table 1 Overview of published papers that applied emergy synthesis on aquaculture production systems between 1991 and 2019

Species and production systems	Objectives	Main outcomes	References
Shrimp mariculture	Evaluate the shrimp pond mariculture in Ecuador	Fuels, services and post-larvae represented the largest emergy expenditure. In addition, pond yields are much higher than the less intensive systems. This may indicate a wasteful process that uses too many resources for the results obtained. It may mean the system is vulnerable to being replaced by less intensive, older systems when prices vary	Odum and Arding (1991)
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 a separated way	Evaluated environmental aspects of integrated production systems of grains, pig and fish in small farms in the South region of Brazil	Integrated system had better emergy efficiency, and it was more sustainable and less stressful to the environment compared to grain, pigs and fish production subsystems in a separated way. Thus, using 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 the 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 inability to exploit local natural resources affected the sustainability of this productive process	Vassallo *et al*. (2007)
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 over 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 analysed 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)

Table 1 (continued)

Species and production systems	Objectives	Main outcomes	References
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 synthesis proved to be a good complement to economic assessment in the evaluation of the production efficiency, environmental impacts, economic benefits, ecological and the sustainability of aquaculture systems	Li *et al*. (2011)
Polyculture of grass carp (*Ctenopharyngodon idellus*) and silver carp *(Hypophthalmichthys molitrix*) in cages, reared with natural food with plankton; Polyculture of grass carp, silver carp and spotted silver carp *(Aristichthys mobilis)* in ponds, reared with feed; Polyculture of grass carp and silver carp in extensive ponds, reared with feed 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 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 mushroom 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)

Table 1 (continued)

Species and production systems	Objectives	Main outcomes	References
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 favourable 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 practised 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 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)

Table 1 (continued)

Species and production systems	Objectives	Main outcomes	References
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 monitoring the environmental impact of fish farming. In addition, the high dependence on external contributions affected the sustainability of fish farming	Zhao *et al*. (2013)
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 synthesis 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 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 systems 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 systems. 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-labour, purchase of fingerlings, fuels, goods and services. Compared with other aquaculture products, oyster aquaculture farms were 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	Williamson *et al*. (2015)

Table 1 (continued)

Species and production systems	Objectives	Main outcomes	References
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)
Tilapia (*Oreochromis niloticus*) cage farming with substrates for periphyton	Evaluated the sustainability of tilapia cage farming, in Brazil. Emergy accounting was utilized to evaluate whether the use of periphyton as a complementary food and the reduction in storage density improve the sustainability of this production system	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 indices evaluated. The use of periphyton to feed cultured fish combined with a reduction in feed use and a decrease in the stocking density promote the sustainability on tilapia cage farming	David *et al.* (2018)

As a consequence, production systems are highly dependent on resources from the economy – mostly fossil-based ones – which cause high pressure on the natural environment by demanding these kinds of resources, and indicated by the environmental loading ratio (ELR) emergy index (Brown & Ulgiati 2004; Zhang *et al*. 2011).

Overall, the reviewed papers showed that traditional intensive aquaculture production systems can hardly have high levels of productivity and at the same time be sustainable (Lima *et al*. 2012), because high productivity is obtained from using large amounts of fossil-based resources, which consequently makes productive systems dependent on resources from the economy. A performance opposite to the one above is shown by those, still traditional, but extensive aquaculture systems that depend on local and more renewable resources, resulting in higher sustainability but with lower productivity.

Aquaculture system efficiency has been mainly based on the mass of aquatic organisms produced per volume of water used during the productive period (Roth *et al*. 2001; Valenti *et al*. 2018). Methodologies currently used to assess aquaculture sustainability do not consider that the intensification of monoculture increases the use of feed per water volume (Garcia *et al*. 2016). Thus, efficiency in aquaculture should reveal more than simply water consumption. At this point, ES appears as an alternative method in estimating system efficiency, because it is able to include the 'quality' of energy through its UEV which represents all the efforts previously made by nature to make the water and feed resources available. Since higher efforts or emergy, mainly from non-renewable sources, are needed to make feed rather than water, feed seems to negatively affect the sustainability of aquaculture (Table 1). In addition, using feed above the recommended levels results in water eutrophication and causes an even higher pressure on the environment. As also identified in the reviewed papers in Table 1, water usually comes from superficial reservoirs or rivers and is labelled as a renewable resource. The quality and source of water are recognized by ES, making it more appropriate in quantifying system efficiency (Odum 2000) than simply accounting for the volume of used water. ES thus reveals new insights into the current ideas about what sustainable aquaculture would be, changing the general idea of water as its 'main villain'.

Evaluating intensive cage farming systems, Vassallo *et al*. (2007) obtained low efficiencies in terms of the unit emergy value (UEV of 2.22E + 06 sej/J), low sustainability (ESI of 0.29), and high environmental load ratio (ELR of 5.00). Similar to other references, these emergy indices show low environmental performance as a characteristic for intensive aquaculture systems, in general. However, specific techno-management practices in extensive systems have been adopted to produce fish similarly to fish growth in natural systems, which *a priori* would increase aquaculture sustainability. For instance, Zhang *et al.* (2011) compared different intensification levels for aquaculture production and found higher sustainability (ESI 4.61) and lower loading ratio ELR (0.38) for the extensive system compared to the semi-intensive one (3.98 and 0.55 for ESI and ELR, respectively), but the efficiency as represented by the UEV still showed to be lower (5.23E + 05 and 4.61E + 06 sej/J). From an economic point of view, the low yields of extensive aquaculture systems reduced the financial returns, making this system limited to local production and consumption of fish and/or farms that seek environmental certification (green labels) to sell their products to a differentiated market.

Integrated aquaculture systems, such as polycultures, are promising alternatives to optimize the use of resources by reducing the dependence on economic inputs (mainly feed) and increasing productivity (Shi *et al.* 2013; Wilfart *et al.* 2013; Cheng *et al.* 2017). Polyculture is a model of production in which more than one non-competitive species from different trophic levels are grown at the same time and culture unit (Boyd *et al.* 2020). In this case, the 'waste' generated by a production chain becomes a 'potential resource' to another, which from a systemic perspective will reduce production costs and emission of pollutants into the environment (Shi *et al.* 2013). For example, Cavalett *et al.* (2006) compared the integrated production of grains, pigs and fish with their production in monoculture systems. Their results showed that the integrated system has higher sustainability, higher efficiency (9.40E + 05 sej/J vs. 3.00E + 06 sej/J), and a lower loading ratio (ELR of 3.13 vs. 3.59) than monocultures.

Usually, food production in integrated systems shows additional advantages besides better emergy indices. For example, Kremen and Miles (2012) found evidence to support the advantages of biologically diversified farming systems in terms of biodiversity conservation, control of arthropod pests, weeds and diseases, pollination services, soil quality maintenance, energy use efficiency and a reduction in global warming potential, resistance and resilience of farming systems to extreme weather events and enhanced carbon sequestration and water-holding capacity in surface soils. As an example of an integrated system in aquaculture, 'aquaponics' that is a combination of intensive aquaculture with soilless plant production (hydroponics) has been recognized as being environmentally friendly. Although using resources effectively (Pinho *et al.* 2017; Palm *et al.* 2018) and presenting potential economic results when applied commercially (Quagrainie *et al.* 2018; Greenfeld *et al.* 2018), aquaponics is often considered as a tool for education and social inclusion (König *et al.* 2018). Since we did not find any type of emergy synthesis of aquaponic production in the scientific literature, efforts on assessing its sustainability are needed.

Aspects that deserve attention when applying emergy synthesis to aquaculture systems

After carrying out a literature review (Table 1), we were able to identify and discuss specific aspects that require attention when applying ES to aquaculture systems. The key aspects are related to the choice of UEV for feed and water input flows, the classification of water input as a renewable or non-renewable resource, the way in which water input is accounted for in emergy tables, and issues related to environmental services and disservices. All these aspects are discussed separately in the next sections for a better understanding.

Feed

The feed accounts for up to 70% of production costs in intensive aquaculture in monoculture systems when traditional economic evaluations (willingness to pay) are carried out (Ayroza *et al.* 2011). According to most of the studies presented in Table 1, feed is also the most expensive item from an ES perspective. This may be related to its energy-intensive production chain, which demands raw materials (fishmeal, blood meal, bone meal, feather meal, soybean meal, corn meal, wheat meal, mineral supplements, and vitamins), machinery, equipment, electric power, vehicles, fossil fuels, etc., to be produced and delivered to aquaculture producers. Detailed information on feed production (including the amount and kind of resources and industrial processes) is scarce, usually because industries consider feed production as confidential material that should be maintained to avoid market losses. As a result, the UEV for feed used in most ES studies is based on outdated data, which would reduce the precision of ES results. This requires studies that update the feed UEV.

Management aimed at reducing feed and increasing the use of natural food, for example phytoplankton, zooplankton, and periphyton, is encouraged (Cheng *et al.* 2017). The use of natural food to supplement fish feeding was evaluated using ES and showed to be a real alternative to increase the sustainability aspects of systems (Zhang *et al.* 2011; David *et al.* 2018). Artisanal feeds, which are locally made by small producers within their own farms, may be an alternative to replace the manufactured feed. Because locally available ingredients are used in the artisanal feeds and a limited number of steps in the production chain are needed compared to manufactured ones, artisanal feed leads to lower dependence on large machinery, fossil fuels and manpower. Another alternative to meet sustainable feeding production is by using Biofloc Technology (BFT). BFT is an intensive aquaculture system technology where microbial communities are stimulated to allow minimal water exchanges, production and availability of *in situ* natural sources of food (Emerenciano *et al.* 2017). As well as the aquaponic system, BFT is usually labelled as sustainable food production (Bossier & Ekasari 2017). However, when considering all the infrastructure and electricity needed to maintain a BFT system, this label is questionable. For both alternatives (artisanal and BFT), to reduce the use of manufactured feed, no papers applying ES to evaluate these two specific productions systems were found in our literature review.

Regarding feeding as one of the most important energetic and/or economic aspects for aquaculture production, inaccuracies in its UEV, even minor ones can cause strong effects on the results of ES. Generally, the UEV chosen by the ES analyst is based on previously published assessments that may not have the same characteristics of the system being evaluated. As the feed represents 4.5% to 76% of the total emergy of intensive aquaculture systems (Table 2), special attention must be given when choosing the feed UEV to increase the accuracy of the study, either for feed or natural food. Differences in feed UEV are mainly related to local food availability, price, nutritional requirement of aquatic species, distance between the industry and ingredient producers, etc. In other words, UEVs can be widely different depending on these aspects.

From the reviewed papers in Table 2, the UEVs for feeding (sej/J, sej/kg and sej/g) showed high variability. For example, it ranges from 3.19E + 04 sej/J for natural food (plankton) to 9.80E + 08 sej/J for feed in salmon farms. This raises doubts about the accuracy of obtained results from those papers, as well the lack of standards for ES applications. We strongly support additional studies towards more precise and/or representative feed UEV for different production systems, species, and locations, since it is the most important input flow in aquaculture ES. Advances were made from a study conducted by Giannetti *et al.* (2019), who showed a linear relationship between energy and UEV, corroborating the hierarchical organization of the biosphere in terms of energy quality, according to the hypothesis of H.T. Odum and also allowing UEV estimates as a first proxy when UEVs are missing. It is important to emphasize that the need to expand the conversion factor database is also a 'temporal' aspect, because when more studies are carried out and the results obtained, more data is available, resulting in more accurate and standardized UEV values. However, emergy analysts who evaluate aquaculture production systems should make additional efforts to estimate and/or evaluate the feed that precisely represents the case in point, rather than using 'borrowed' UEVs from the literature and generating uncertainties. This issue also happens in other methods such as life cycle assessments, ecological footprint and embodied energy analysis. Nevertheless, while larger numbers of precise UEVs are still missing, an uncertainty analysis could be applied in ES (Li *et al.* 2011; Hudson & Tilley 2014).

Ecosystem services and disservices

Another aspect that deserves attention in sustainability assessments is the ecosystem services and disservices (ES&D) (MEA 2005; Shah *et al.* 2019). This concept has become popular in the field of environmental research and policymaking in the past 20 years, since it was realized that food production systems can provide benefits beyond food (Aubin *et al.* 2019; Custódio *et al.* 2020). These production systems are managed mainly to provide food, fibre, and energy. At the same time, they can deliver a variety of ecosystem services, such as water quality regulation, climate regulation, and carbon storage, which indirectly controls greenhouse gas emissions. On the contrary, food production systems may also cause soil erosion, nitrogen leaching, and habitat deterioration, which are considered as ecosystem disservices (Shah *et al.* 2019).

Identifying ecosystem services and disservices (ES&D) from aquaculture production systems is an important and necessary aspect to differentiate those systems that consider their environmental, economic, and social benefits (services) and the negative impacts (disservices) on the society (Aubin *et al.* 2019; Shah *et al.* 2019). Identifying, defining, and quantifying ES&D can be considered as vital when dealing with the Earth's biocapacity to support human-made systems. The amount and/or value of ES&D should be accounted for in sustainability analyses, such as emergy synthesis, to better reflect the performance of a production system and define ways to make it more sustainable. Systems that provide ecosystem services should receive some support, while those that cause disservices should be responsible for the damage caused (Custódio *et al.* 2020).

Including ES&D in the revenue or in the production costs has been a challenge for economists and environmental scientists involved with aquaculture sustainability studies (Valenti *et al.* 2018). Although some authors have suggested ways to measure and value ES&D (Table 3), there is a lack of a conceptual framework supporting the identification and linkage of ES&D with different aquaculture systems, as well as its integration with sustainability assessment tools (Kim *et al.* 2017; Alleway *et al.* 2019; Willot *et al.* 2019). Within this context, there is an opportunity to use emergy synthesis as a potential tool to provide this framework (Ortega & Bastianoni 2015).

The application of ES&D concepts is recent in aquaculture sustainability assessments (Kim *et al.* 2017; Alleway *et al.* 2019), which explains the existing lack of standards concerning their application in ES studies. Through our literature review and experience in the field of aquaculture

Table 2 Unit emergy values (UEVs) for feeding as used in the papers presented in Table 1

Reference	Specific characteristic	Origin of feeding	Feeding UEV	(sej/unit)	Total emergy flow (sej/year)	Feeding representatively (%)
Odum and Arding (1991)	Shrimp production in ponds	Feed	1.31E + 05	sej/J	2.18E + 21	19.71
Odum (2000)	Salmon pond culture	Organic	2.09E + 13	sej/kg	1.94E + 20	5.05
Cavalett *et al*. (2006)	Extensive fish production in ponds	Not used	-	-	1.95E + 09	-
Vassallo *et al*. (2007)	Marine inshore fish farming	Organic	1.00E + 06	sej/J	1.60E + 18	11.31
Li *et al*. (2011)	Eel pond farm	Forage	8.32E + 11	sej/¥	2.14E + 17	76.17
	Weever pond farm	Forage	8.32E + 11	sej/¥	3.04E + 17	52.30
	Ophicephalus and mullet pond farming	Forage	8.32E + 11	sej/¥	2.37E + 17	67.09
Zhang *et al*. (2011)	Cage fish farming	Natural (plankton)	3.19E + 04	sej/J	2.74E + 17	41.24
	Intensive pond fish farming	Feed	1.31E + 05	sej/J	1.07E + 17	30.75
	Semi-natural extensive pond fish farming	Not used	–	–	7.10E + 16	–
Zhang *et al*. (2012)	Semi-natural extensive pond fish farming	Not used	–	–	7.16E + 16	–
Lima *et al*. (2012)	Semi-intensive pond	Feed	2.05E + 09	sej/g	5.84E + 16	7.1
	Organic pond	Not used	–	–	5.16E + 16	–
Wilfart *et al*. (2013)	Salmon	Feed	9.80E + 08	sej/J	2.63E + 18	45.63
	Extensive pond farming	Wheat	1.20E + 06	sej/J	9.10E + 17	63.74
	Semi-extensive pond farming	Feed + Wheat	1.20E + 12	sej/kg	2.80E + 17	12.96
Garcia *et al*. (2014)	Intensive tilapia cage farming	Feed	1.00E + 06	sej/J	1.09E + 17	76.43
Wang *et al*. (2015)	Indoor sea cucumber farming	Feed	1.92E + 12	sej/kg	8.32E + 18	21.15
	Semi-intensive sea cucumber farming	Feed	1.92E + 12	sej/kg	1.91E + 17	4.52
	Extensive sea cucumber farming	Not used	–	–	1.59E + 17	–
Williamson *et al*. (2015)	Oyster farming	Natural (microalgae)	5.00E + 04	sej/J	2.96E + 13	16.42
David *et al*. (2018)	Traditional cage system	Feed	9.96E + 04	sej/J	3.80E + 15	67.08
	Traditional cage system with periphyton	Natural (periphyton)	2.71E + 03	sej/J	2.45E + 15	51.82
	Lower stocking density with periphyton	Natural (periphyton)	2.71E + 03	sej/J	1.49E + 15	38.77

and emergy synthesis, we identified some aspects that require more research to overcome this lack of standards. Firstly, there is a need for a clear definition of the aquaculture's ES&D. Efforts in this direction were made by Aubin *et al*. (2019), who could be used as the first reference. They provided a list of ES&D from a general perspective, although it is worth mentioning that the ES&D differs for specific production systems. Secondly, there is a clear need regarding how to quantify ES&D. As presented in Table 3, ES&D are mostly quantified in economic units and then considered in emergy synthesis; however, the inherent subjectivities behind economic methods require more objective (biophysical) approaches. Nevertheless, until a standardized and biophysical based approach is established, evaluating ES&D from an economic perspective would be a way to recognize their importance when dealing with sustainability assessments. Thirdly, there is a clear need on how to account for ES&D within ES. In the literature, there is a tendency to consider ecosystem services as a coproduct (an emergy output) and seeing it as positive aspect, while disservices are usually considered as a system input (an emergy input) and seeing it as a negative aspect. Both are usually estimated under economic approaches, and their classification as a non-renewable (N), renewable (R) or economic resources (F), as necessary within emergy synthesis, still lacks understanding, however relevant papers are still scarce and do not allow in-depth evaluations.

A balance between ecosystem services and disservices is necessary to determine, beyond the magnitude of the benefit or damage, environmental debit or credit generated by the production system (Ortega & Bastianoni 2015). Similar to other anthropic production systems, modern aquaculture is challenged to be efficient, highly productive and, at the same time, to cause a low load on the natural environment. Studies on ES&D in aquaculture are recent and regulatory agencies are still unaware of how to use them in

Table 3 Ecosystem services and disservices of aquaculture production systems

Items	Quantification approach	Inclusion approach	References
Ecosystem services			
Climate regulation service	Greenhouse gas balance	Carbon credit	Boyd *et al*. (2010), Thompson *et al*. (2014), Malik *et al*. (2015), Alleway *et al*. (2019), Aubin *et al*. (2019), Custódio *et al*. (2020)
Water purification	Removal of N, P in the water and indicators of eutrophication reduction	Payment for environmental services based on water quality	Alleway *et al*. (2019), Aubin *et al*. (2019), Custódio *et al*. (2020)
Recreation/ Ecotourism/ Environmental Education	Number of visitors	Tax of visitation	Alleway *et al*. (2019), Aubin *et al*. (2019), Custódio *et al*. (2020)
Ecosystem disservices			
Greenhouse gas emission	Greenhouse gas balance	Tax of carbon emission	Boyd *et al*. (2010), Thompson *et al*. (2014), Malik *et al*. (2015), Alleway *et al*. (2019), Aubin *et al*. (2019), Custódio *et al*. (2020)
Eutrophication	Discharge of N, P in the water and indicators of eutrophication	Tax of eutrophication based on the cost to remove these nutrients from water	Verdegem (2013), Troell *et al*. (2017)
Effluent contamination by drugs, hormones, and chemicals	Discharge of pollutants in water bodies	Tax of pollution based on the cost to remove these pollutants	Vignesh *et al*. (2011), Lozano *et al*. (2018)

public policies. Worst situations happen when society does not understand the concepts and/or physical relations of ES&D on limits of growth – maybe due to the neoclassical economic theories behind societal intellectual development. At this point, besides a change in development theories we teach our students another important aspect, which is to have more discussions in the scientific arena on ES&D and their importance when dealing with sustainability assessments. Here, discussions about the lack of existing standards in relation to ES&D in the emergy synthesis are of paramount importance and, as suggested by Ortega and Bastianoni (2015), the International Society for the Advancement of Emergy Research (ISAER) has an important role in improving its database with energy diagrams (models), description of input flows, renewability and supply of updated UEVs for a large number of production systems.

Water

Concerning water, our literature review showed the existence of three main issues when applying emergy synthesis on aquaculture: (i) outdated UEVs; (ii) classification of water as a renewable or non-renewable resource; (iii) the way in which water is accounted for in emergy tables. Besides water being the fundamental resource for all aquaculture production systems and vastly used in aquaculture emergy synthesis, there is a lack of updated values for water UEV, because it has remained almost unchanged over the last years (Table 4). Thus, water UEV must be revisited and updated, also by considering the advances in emergy analysis and water treatment technologies over the last twenty years. Additionally, clear criteria in labelling water as a renewable (R) or non-renewable (N) resource is generally missing. Notwithstanding, water is usually evaluated or quantified in inappropriate ways by considering the total volume of water that flows through the system and not the water really used. Since water is probably the most used (in mass or volume) resource in aquaculture studies, wrong interpretations of water resource classification, the way in which it is evaluated, and its UEV would result in high inaccuracies on the final numbers and lead to wrong interpretations.

By definition, the label ‘renewable’ depends on the extraction rates, in other words, to be renewable a resource cannot be extracted at higher rates than its natural reposition (Valenti *et al.* 2011). Deep water (groundwater and aquifers) takes, on average, a long time to be renewed, and thus it is usually labelled as a non-renewable resource and has high UEV (Cavalett *et al.* 2006; Wilfart *et al.* 2013). On the other hand, surface waters (rain, rivers, spring water and seawater) require less effort from nature to be cycled and are used at higher rates than groundwater, resulting in lower UEVs and are labelled as a renewable resource (Odum 2000; Vassallo *et al.* 2007; Li *et al.* 2011; Wang *et al.* 2015; Cheng *et al.* 2017). These concepts and approaches for water classification are usually misunderstood by some emergy analysts when assessing aquaculture systems, since it is not hard to find published papers in which emergy analysts do not provide clear criteria in labelling water resources, thus raising doubts about the obtained results.

Concerning the way water is accounted for in emergy tables, we provide our comments in accordance to the different kinds of aquaculture production management. Figure 2 shows the aquaculture system most often described as traditional during our literature review, which is the system with untreated water renewal prior to disposal. Typically, these are open systems (generally in natural water bodies such as oceans, estuaries, bays, lakes, rivers) or semi-closed systems (those in which water flows through the system once and it is subsequently discharged). Water sources can change depending on the local availability (i.e. rivers or groundwater). In these systems, water flows into the system to fill the ponds and/or cages where the aquaculture production happens. The volume of water flowing in is the same as that of flowing out, but the latter has lower quality with higher concentrations of nutrients and organic compounds. Since these systems rarely have a water treatment process unit, this low-quality water is directly disposed into the natural water bodies, potentially causing a disservice to the environment and society. As we found during our literature review, water is accounted for and classified as renewable (R) or non-renewable (N) in the emergy tables according to its volume and source (river or groundwater), as shown by the input flows in red shown in Figure 2. However, according to the definition of solar emergy – 'available solar energy used up directly and indirectly to make a service or product' – we acknowledge that this procedure in accounting water resources is misleading and should be corrected. The output flow is generally not considered in ES of aquaculture systems and, when considered, is quantified using economic approaches and accounted for as a service (S), as discussed in the previous section.

Figure 3 provides a more aligned perspective with the definition of emergy, in which aquaculture systems should be seen. In this case, a water treatment process is present since the production system is responsible for improving the effluent water quality before discharging the effluent into the natural environment. The treatment must achieve, at least, the same quality standards of the water before it enters the production system. In this type of production system, the amount of water that must be accounted for in emergy tables is that evaporated and embodied in the fish bodies (output flows in red in Figure 3), both classified according to the water source (renewable or non-renewable, R&N). Besides the amount of water, all emergy for the water treatment also needs to be accounted for in the emergy tables, and it is classified as economic resources (materials and services, M&S). In a case where there is no water treatment process, which is often found in rural aquaculture systems (Figure 2), the emergy of water treatment must be estimated accordingly and then accounted for in emergy tables.

Other aquaculture systems that deserve attention are those with limited water renewal, such as Recirculation Aquaculture Systems (RAS) and aquaponic systems. Figure 4 shows an aquaponic system, in which besides producing fish, the effluent water rich in nutrients and organic matter is used to produce vegetables in a hydroponic way.

Table 4 Unit emergy values (UEVs) and classification of water resources as usually found in emergy literature applied to aquaculture production systems

Reference	Water Source	Classification	UEV (sej/J)	Original source for water UEV
Odum and Arding (1991)	Sea water	Renewable	1.54E + 04	Estimated
Odum (2000)	Estuarine	freshwater	Non-	renewable
1.19E + 11	Estimated			
Cavalett *et al.* (2006)	Ground water	Non-renewable	2.55E + 05	Odum and Arding (1991)
Vassallo *et al.* (2007)	Rain	Renewable	1.54E + 04	Odum and Arding (1991)
Li *et al.* (2011)	River water	Renewable	5.01E + 04	Campbell *et al.* (2005)
Zhang *et al.* (2011)	Ground water	Non-renewable	8.06E + 04	Odum (1996)
Zhang *et al.* (2012)	Ground water	Non-renewable	8.06E + 04	Odum (1996)
Lima *et al.* (2012)	Estuarine	freshwater	Non-	renewable
8.10E + 04	Brown and Ulgiati (2004)			
Wilfart *et al.* (2013)	Ground water	Non-renewable	1.60E + 05	Odum and Arding (1991)
Garcia *et al.* (2014)	Spring water	Renewable	1.66E + 05	Buenfil (2001)
Wang *et al.* (2015)	Not	considered	–	–
Williamson *et al.* (2015)	Not	considered	–	–
David *et al.* (2018)	Rain	Renewable	2.36E + 04	Odum (2000)

This system recycles almost all the water demanded in the beginning of the production cycle, losing water exclusively embodied in the harvested fish and vegetables, and due to evapotranspiration. For this system, only the water loss should be accounted for in the emergy tables (output flows in red in Figure 4) and classified as renewable (R) or non-renewable (N) according to its source.

We have no intention to present all different kinds of aquaculture systems, although most of them are derived from the two presented in Figures 3 and 4 and use the same concepts. Most important is that emergy analysts provide high-quality energy diagrams to better understand and communicate how the system under study works, and always remembering that there is a method as a backbone (emergy accounting) with definitions and rules that must be respected.

Emergy synthesis results as support for policies in aquaculture

The results of the sustainability evaluation by the emergy synthesis can serve as a basis for strategies to encourage sustainable practices. Knowing the transformity concept, distinguishing renewable from non-renewable resources and transforming all inputs and outputs into a single unit (emergy) lead to quantifying the sustainability of any product or service and the differentiation between more and less efficient production (Cavalett *et al.* 2006). These differentiations can generate future identifications of aquaculture products through seals and certifications. By doing this, consumers will be able to choose their products based on a categorization of sustainability (McClenachan *et al.* 2016).

The literature on ES for aquaculture proposes creating or adapting public policies that encourage farmers to adopt sustainable practices in their properties and benefit those who already do this (Cavalett *et al.* 2006; Zhang *et al.* 2012). ES could also guide the regulations for using natural resources and the support capacity of aquaculture systems (Garcia *et al.* 2014; Cheng *et al.* 2017). Considering the results of emergy synthesis, it would be possible to create specific lines of credit for sustainable production systems, and to pay farmers who generate positive impacts to society through a Payment for Ecosystem Services policy. In situations such as these, the aquaculture producer could, for example receive benefits by water remediation and by executing an efficient productive system.

Another way of using ES for public policymaking is to encourage investments in more sustainable aquaculture systems by eliminating or reducing some taxes (Lomas *et al.* 2008). The change in taxes for other industries is already a reality. For example, the lower taxation of vehicles with less emission of pollutants or the reduction in taxes (up to 100% reduction) for farmers that adopt sustainable practices, such as planting trees on the borders of the production systems, reusing the water or harvesting rainwater, etc. Government programs can also promote aquaculture sustainable production systems by legislating the preference to purchase their products for the supply of public institutions.

Punishment for ‘bad producers’ could be also guided by ES results, that is public policies can be developed to add tax to those who insist on practising unsustainable management. Using the Emergy Exchange Ratio (EER), an ES index which measures the emergy exchanged in a trade or purchase (what is received to what is given) (Brown & Ulgiati 2004), is a way of measuring the monetary value of this punishment. David *et al.* (2018) evaluated different managements for tilapia reared in cages and showed that in the alternative system, with a reduction of 50% of the daily feed and using periphyton as a complementary food, the EER was 0.78. With this result, they showed that tilapia reared in this way may have its sales value reduced by 22% as compared to the traditional system. Under the policy of punishment, this difference in the sale value would be due

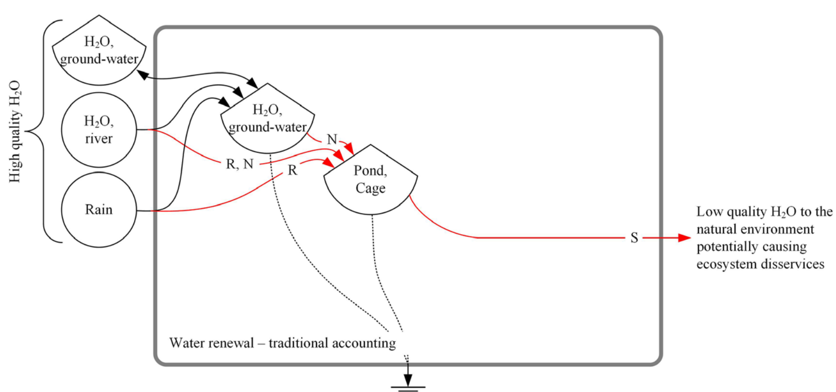

Figure 2 Energy diagram of traditional aquaculture systems as usually found in the emergy literature. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable; S, service.

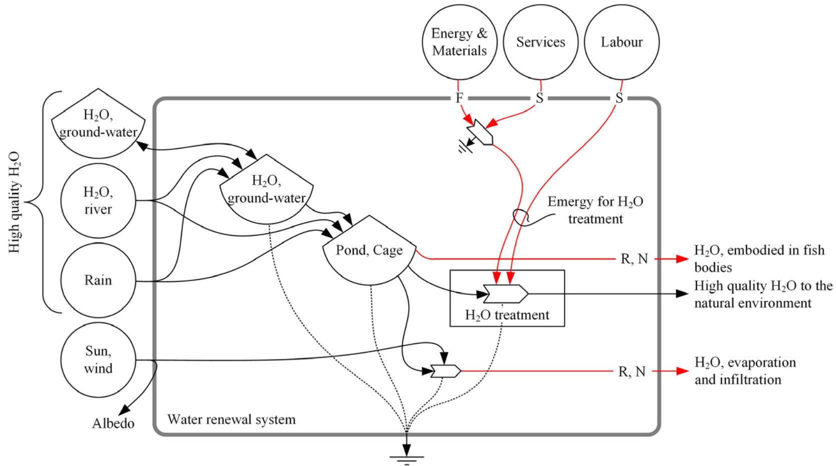

Figure 3 Energy diagram of traditional aquaculture systems with water renewal and treatment as usually found in the emergy literature. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable; M, materials; S, service.

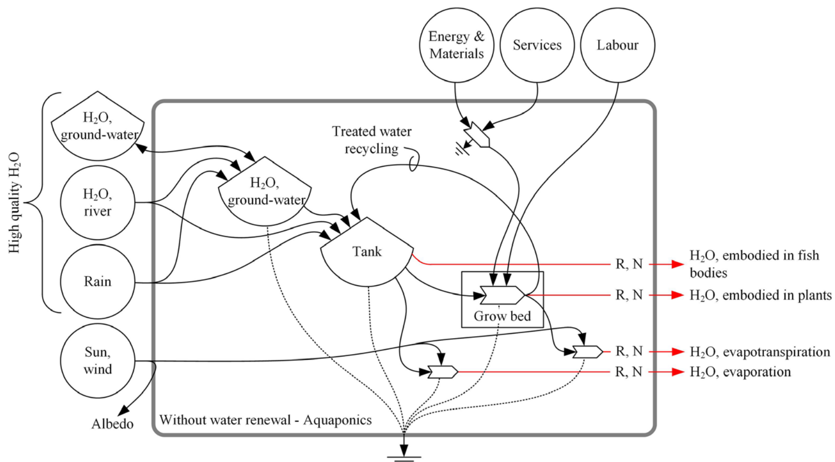

Figure 4 Energy diagram of Recirculation Aquaculture Systems (RAS) combined with hydroponic system, also known as aquaponics system, with limited water renewal. Symbols from Odum (1996). Legend: R, renewable; N, non-renewable.

to the additional taxes for the producers that apply the traditional managements.

In summary, emergy synthesis for aquaculture can guide public policies along two different lines: one that encourages more sustainable producers through specific lines of credit or tax reduction or one that punishes producers who do not use sustainable practices. The decision on which policy to apply will depend on the local and cultural conditions of each community. Nevertheless, the entire aquaculture production chain must be evaluated. In addition to public policies, the understanding and incorporation of sustainability concepts and the interpretation of ES results by the productive sector and society can guarantee the resilience of aquaculture activity over time. For this, it is extremely important that extension workers receive quality training to transfer these new approaches to producers, especially to those with low access to resources and information.

Final remarks

Aquaculture systems receive special attention due to their importance in producing proteins to feed the increasing world population. Besides economic and technical aspects, sustainability issues of aquaculture production systems also gain more attention in a world with reduced biocapacity. The most sustainable systems must be identified and supported through public policies and economic incentives.

Besides other methods, emergy synthesis (ES) is a powerful tool for assessing the sustainability of production systems due to its systemic perspective and donor side approach that allows it to quantify natural and economic resources based on their energy quality. ES of aquaculture systems is still in its infancy, which is expressed by the few number (16) of papers identified according to our literature review for the period from 2000–2020. The published papers clearly showed that feed is the most important resource of aquaculture systems, ranging from 4 to 70% of the total emergy required. It is also emphasized that there is a need for more renewable resources, in which natural feed has a huge potential. Additionally, aquaculture systems based on monoculture have lower emergy performance than the integrated ones (polyculture), indicating the latter as a preferable choice towards more sustainable fish protein production.

Another important result from this work was to identify aspects that deserve attention by emergy analysts when studying aquaculture production systems. The identified methodological shortcomings, lack of standards or misunderstandings are as follows: (i) outdated and/or not accurate unit emergy values for feed and water resources; (ii) the procedures used when classifying water input as renewable or non-renewable; (iii) the procedures used when accounting for water input in emergy tables; (iv) the identification and consideration of ecosystem services and disservices resulting from aquaculture. Since feed and water are the main input flows of aquaculture production systems, special attention to these should be given by emergy analysts to avoid misleading results and interpretations.

Regarding policy implications, ES of aquaculture systems can help to support those systems to become more sustainable through different ways, including economic incentives (tax reduction and loans with reduced interests), and establishing the so-called ‘labels of sustainability’ to increase market acceptance. All these efforts can directly and indirectly push those less sustainable systems to increase their performance, making sustainable designs as a rule as envisioned by the United Nations Sustainable Development Goals in the 2030 Agenda.

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