UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CENTRO DE AQUICULTURA DA UNESP

Benchmarking **da sustentabilidade ambiental de fazendas de tilápia do Nilo (*Oreochromis niloticus*) sob diferentes escalas de produção instaladas em represas e reservatórios no estado de São Paulo**

Naor Silveira Fialho

Jaboticabal, São Paulo

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SUMÁRIO

LISTA DE ABREVIAÇÕES E SIGLAS

(ADG)	Average daily gain
(AOM)	Accumulation of Organic Matter
(AP)	Accumulation of Phosphorus
(C)	Use of Carbon
(CONAMA)	Environment National Council
(CP)	Crude protein
(DO)	Dissolved oxygen
(E)	Use of Energy
(EC)	Efficiency in the Use of Carbon
(EE)	Efficiency in the Use of Energy
(EN)	Efficiency in the Use of Nitrogen
(EP)	Efficiency in the Use of Phosphorus
(ESI)	Environmental Sustainability Indicators
(FBW)	Final body weight
(FCR)	Feed conversion ratio
(GCP)	General Chemical Pollution
(GE)	Gross energy
(IBW)	Initial body weight
(N)	Use of Nitrogen
(NFE)	Nitrogen-free extract
(P)	Use of Phosphorus
(PEn)	Potential of Nitrogen Eutrophication
(PEp)	Potential of Phosphorus Eutrophication
(PGW)	Potential of Global Warming

(PH)	Pollution by Hormones
(PHM)	Pollution by Heavy Metals
(POP)	Potential of Organic Pollution
(PRE)	Proportion of Renewable Energy
(PU)	Production Actually Used
(RFS)	Risk of Farmed Species
(RSS)	Residual sum of squares
(S)	Use of Space
(TGC)	Thermal-unit Growth Coefficient
(W)	Dependence on Water

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INTRODUÇÃO GERAL

Atualmente, a sustentabilidade dos processos de produção de alimentos vem sendo debatida, especialmente no âmbito ambiental. Na aquicultura, existe essa preocupação sobre as práticas sustentáveis para produção de organismo aquáticos, e como deve ser medida a sustentabilidade desta atividade. A aquicultura é um dos setores produtores de alimentos que mais cresce no mundo (DAVID *et al.,* 2017a, 2017b; ENGLE, 2019). No Brasil, existe uma expectativa de crescimento da produção de peixes de 104% até 2025, atingindo 1.145.000 toneladas de peso vivo (FAO, 2016). São Paulo é um dos estados de maior destaque no país, sendo o segundo maior produtor de peixes (PEIXE BR, 2019). Neste cenário, a tilápia do Nilo (*Oreochromis niloticus*) é a principal espécie produzida, representando quase 95% de todos os peixes cultivados no estado de São Paulo (PEIXE BR, 2019).

A aquicultura ambientalmente sustentável é baseada no uso racional dos recursos naturais no processo de produção (GONÇALVES, 2017). A principal característica da produção sustentável é assumir que a natureza é finita. Além disso, cada geração deve deixar uma herança de recursos naturais equivalentes ou superiores ao que eles receberam para a próxima geração (KIMPARA *et al.*, 2012; VALENTI *et al.*, 2018). No entanto, as externalidades ambientais geradas pelo ecossistema da aquicultura são uma preocupação para alcançar o desenvolvimento sustentável da atividade. Externalidades ambientais são os impactos da produção sobre terceiros que não estão diretamente envolvidos com a atividade, podendo ser positivas ou negativas (MOTTA, 1997). Os seres humanos não consomem todo o organismo cultivado. As partes restantes se tornam resíduos e são descartadas. Assim, grande parte da energia e material que é fornecida aos organismos cultivados está incorporada nesses resíduos (BUENO *et al.*, 2017; VALENTI *et al*., 2018). Também há parte dos materiais e energia que não são incorporados pelo organismo. Um dos principais materiais é a ração utilizada. Esses materiais, que não são incorporados, são absorvidos pela biota natural associada à cultura, acumulada no sistema como sedimento ou dispersa no ambiente circundante (DAVID *et al.*, 2017a, 2017b). Portanto, o não gerenciamento dessas externalidades pode comprometer a sustentabilidade ambiental dos ambientes aquáticos.

Medir a sustentabilidade dos sistemas utilizados, das técnicas de manejo aplicados, e das novas tecnologias que estão sendo geradas são essenciais para alcançar uma aquicultura ambientalmente sustentável (KIMPARA *et al.*, 2012). Nesse contexto, vários pesquisadores (ODUM, 1986, SCIENCEMAN, 1987; REES & WACKERNAGEL, 1996; PAPATRYPHON, 2004; ADGER, 2000; WARHURST, 2002; BOYD *et al.*, 2007; VALENTI *et al.,* 2018) têm apresentado diferentes métodos para avaliar a sustentabilidade como: análise do ciclo de vida, análise emergética, pegada ecológica, indicadores de sustentabilidade e análise de resiliência, que são os métodos mais usados para medir a sustentabilidade da aquicultura (KIMPARA *et al.*, 2012). Dentre esses, destaca-se o método de grupo de indicadores de sustentabilidade, formulado especificamente para a aquicultura (VALENTI *et al.*, 2018).

Os indicadores de sustentabilidade ambiental (ISA) podem ser utilizados no gerenciamento de externalidades ambientais (VALENTI *et al.*, 2018). Os indicadores fornecem valores que simplificam um fenômeno mais complexo e resumem as características de um sistema de maneira simplificada. Esses são combinados em um índice que pode ser usado na comparação de diferentes sistemas ou no mesmo sistema ao longo do tempo (VALENTI *et al*., 2018). Essa ferramenta permite fazer projeções de curto prazo, apresenta novas soluções para resolver os problemas atuais e ajuda a melhorar a sustentabilidade da aquicultura (NESS *et al.*, 2007; PROENÇA, 2013).

No entanto, é necessário adaptar e padronizar essa ferramenta, os indicadores de sustentabilidade, para diferentes modalidades e situações da aquicultura. A padronização permitirá realizar uma comparação e gerar um produto, que seja aplicável e auxilie os tomadores de decisão. Isto pode ser realizado por meio do processo de *benchmarking*, o qual consiste em comparar o desempenho de uma organização com outros grupos ou padrões aceitáveis (GIACOMINI, 2008; MCDOUGAL, 2012). Essa função serve para identificar os pontos fortes e fracos de uma operação, melhorando resultados ou desempenho de forma incremental ao longo do tempo (MCDOUGAL, 2012).

Portanto, estudos que permitem avaliar o *benchmarking* da sustentabilidade ambiental, utilizando informações obtidas por meio dos ISA, podem auxiliar os gestores na avaliação de diferentes cenários para calcular a eficiência da produção. Diante do exposto, o objetivo deste trabalho consistiu na aplicação dos ISA para avaliar o *benchmarking* de sustentabilidade ambiental de fazendas comerciais com diferentes escalas de produção de tilápia do Nilo (*Oreochromis niloticus*), criadas em barragens e reservatórios no estado de São Paulo.

Dessa forma, a abordagem do *benchmarking* ambiental se tornará um padrão que poderá orientar gerentes, produtores e agências ambientais no planejamento e gestão de empresas aquícolas, visando o desenvolvimento de uma aquicultura sustentável e responsável.

Essa dissertação foi redigida sob a forma de artigo científico. As citações e referências foram formatadas de acordo com as normas do periódico Ecological Indicators, ao qual pretendemos submetê-lo após a defesa.

RESUMO

O *benchmarking* é um processo que permite comparar empresas e seus processos visando identificar oportunidades de melhoria e estratégias para atingir determinado objetivo. Neste contexto, foi aplicado indicadores de sustentabilidade ambiental (ISA) para avaliar o *benchmarking* ambiental de fazendas comerciais com diferentes escalas de produção da tilápia do Nilo (*Oreochromis niloticus*), criadas em represas e reservatórios nas regiões do Vale do Ribeira e Paranapanema, estado de São Paulo. O estudo foi realizado em quatro pisciculturas (A, B, C e D) com escalas de produção de 9,5 a 150 toneladas por ano. Foram monitorados três lotes em cada fazenda, durante um ciclo de produção, com durações variando entre 189 a 263 dias, totalizando doze unidades amostrais de *O. niloticus*. Durante o cultivo, foram coletadas amostras de água, sedimentos, peixes, rações e gases de efeito estufa que foram utilizadas para calcular os ISA. Estes foram divididos em cinco critérios: uso de recursos naturais; eficiência no uso de recursos; liberação de poluentes e subprodutos não utilizados no meio ambiente; poluentes acumulados no fundo do corpo d'água; conservação da diversidade genética e da biodiversidade. Cada ISA foi convertido em uma escala de performance. Os dados dos ISA junto com dados da literatura foram usados para desenvolver um valor de “referência” para cada ISA, permitindo a realização do *benchmarking* ambiental. As propriedades que alcançaram os melhores índices de sustentabilidade ambiental foram as fazendas B e C (82), o pior índice foi a fazenda D (70) e a fazenda A obteve o índice 76. A fazenda C foi influenciada pelo uso de energia, nitrogênio, fósforo e carbono, que foi em média 17% menor em relação às outras fazendas, e pela maior eficiência no uso de nitrogênio e fósforo (32,7% e 23,6%, respectivamente). A fazenda B foi influenciada pelo menor acúmulo de fósforo e matéria orgânica (1 e 90 kg/t, respectivamente). A fazenda D foi influenciada pelos altos níveis de fósforo e matéria orgânica acumulados (10 e 723 kg/t, respectivamente). O uso do ISA foi adequado para realizar o *benchmarking* ambiental e permitiu atingir um valor de referência para os principais ISA. O *benchmarking* demonstrou ser eficiente com a utilização dos ISA para alcançar uma aquicultura mais sustentável.

PALAVRAS-CHAVE: aquicultura, *benchmarking*, indicadores ambientais, tanque-rede, sustentabilidade ambiental.

ABSTRACT

Benchmarking is a process that allows comparing companies and their processes to identify improvement opportunities and strategies to achieve a certain goal. In this context, environmental sustainability indicators (ESI) were applied to assess the environmental benchmarking of commercial farms with different Nile tilapia (*Oreochromis niloticus*) production scales, created in dams and reservoirs in the "Vale do Ribeira" and Paranapanema regions, state of São Paulo. The study was conducted in four fish farms (A, B, C and D) with production scales from 9.5 to 150 tons per year. Three batches were monitored on each farm during a production cycle, with durations ranging from 189 to 263 days, totaling twelve sample units of *O. niloticus*. During cultivation, samples of water, sediment, fish, feed and greenhouse gases were collected and used to calculate the ESI. These indicators were divided into five criteria: the use of natural resources; efficiency in the use of resources; release of pollutants and unused by-products to the environment; pollutants accumulated on the bottom of the water body; conservation of genetic diversity and biodiversity. Each indicator was converted into a performance scale. Data of ESI obtained from each evaluated farm and the literature review were used to develop a "standard" value, allowing performing the environmental benchmarking of the farms. The farms that achieved the best environmentally sustainable indexes were farms B and C (82), the worst was farm D (70), and farm A achieved the index 76. Farm C was influenced by the use of energy, nitrogen, phosphorus, and carbon, which was on average 17% lower than the other farms, and by the highest efficiency in the use of nitrogen and phosphorus (32.7% and 23.6%, respectively). Farm B was influenced by the lowest accumulation of phosphorus and organic matter (1 and 90 kg/t, respectively). Farm D was influenced by the high levels of accumulated phosphorus and organic matter (10 and 723 kg/t, respectively). The use of ESI was adequate and effective to apply the environmental benchmarking and allowed to achieve a reference value for the main ESI of Nile tilapia farms in reservoirs and dams. The environmental sustainability index and benchmarking have proven to be the way to use ESI to achieve more sustainable aquaculture.

KEY-WORDS: aquaculture, benchmarking, environmental indicators, net-cage, environmental sustainability.

1.INTRODUCTION

Nowadays, there is an on-going and considerable debate over environmental sustainability, mainly related to food production. On aquaculture, there is also this concern over what environmental sustainable and responsible managed aquaculture is, and how it should be measured. Aquaculture is one of the fastest-growing food-producing sectors in the world (DAVID *et al.*, 2017a, 2017b; ENGLE, 2019). In Brazil, there is an expectation of growth in fish production of 104% up to 2025, reaching 1,145,000 tonnes live weight (FAO, 2016). The state of São Paulo is highlighted for being the second-largest fish producer in the country (PEIXE BR, 2019). Nile tilapia (*Oreochromis niloticus*) is the main species produced, representing almost 95% of all fish cultivated in the state (PEIXE BR, 2019).

Environmentally sustainable aquaculture is based on the rational use of natural resources in the production process (GONÇALVES, 2017). The main characteristic of sustainable production is to assume that nature is finite. Besides, each generation should leave an inheritance of natural resources equivalent to or greater than the one that they received for the next (KIMPARA *et al.*, 2012; VALENTI *et al*., 2018). However, the environmental externalities generated by aquaculture ecosystem are a concern for achieving sustainable development of the activity. Environmental externalities are the positives and/or negatives impacts of production on third parties that are not directly involved with the activity (MOTTA, 1997). Humans don't consume the whole farmed organisms. The remaining parts become waste and are discarded. Much of the energy and material that are provided are not incorporated by the reared organism and are embodied in these wastes (BUENO *et al.,* 2017; VALENTI *et al.*, 2018). One of the main materials used is the feed, which is not fully incorporated by the farmed organism and is absorbed by the natural biota associated with the culture, accumulated at the system as sediment, or dispersed to the surrounding environment (DAVID *et al.*, 2017a, 2017b). Therefore, failure to manage these externalities can compromise the environmental sustainability of aquatic environments.

Measuring the sustainability of the systems used, of the management techniques applied, and of the new technologies that are being generated are essential to achieve environmentally sustainable aquaculture (KIMPARA *et al.*, 2012). In this context, several researchers (ADGER, 2000; BOYD *et al*., 2007; ODUM, 1986, 1988; PAPATRYPHON, 2004; REES & WACKERNAGEL, 1996; SCIENCEMAN, 1987; VALENTI *et al.*, 2018; WARHURST, 2002) are using different methods to evaluate the sustainability. Life-cycle assessment, emergy analysis, ecological footprint, sustainability indicators, and resilience analysis are the most used methods to measure aquaculture sustainability (KIMPARA *et al*., 2012). Among them, the group of sustainability indicators was formulated specifically for the aquaculture systems (VALENTI *et al.*, 2018).

Environmental sustainability indicators (ESI) can also be used in the management of environmental externalities (VALENTI *et al*., 2018). Indicators provide values that simplify a more complex phenomenon and summarize characteristics of a system in a simplified way. These indicators are combined into an index that can be used in the comparison of different systems or the same system over time (VALENTI, 2008; VALENTI *et al*., 2018). This tool allows making short-term projections, introduces new solutions to solve current problems and helps to upgrade the aquaculture sustainability (NESS *et al.*, 2007; PROENÇA, 2013).

However, it is necessary to adapt and standardize this tool, i.e. sustainability indicators, for different aquaculture modalities and situations. Standardization is going to allow the comparison and the generation of a product, which is applicable and helps the decision-makers. This can be accomplished through *benchmarking*. *Benchmarking* is the act of comparing an organization's performance to other groups or acceptable standards (GIACOMINI, 2008; MCDOUGAL, 2012). This function serves to identify the strengths and weaknesses within an operation, improving results or performance incrementally over time (MCDOUGAL, 2012).

Thus, studies that allow environmental sustainability benchmarking, using information obtained through ESI, can assist managers with the evaluation of different scenarios to appraise the production efficiency. In light of the above facts, the objective of this work was to apply environmental sustainability indicators to evaluate the environmental sustainability benchmarking of commercial farms with different production scales of Nile tilapia (*Oreochromis niloticus*), raised in dams and reservoirs in the state of São Paulo. In this way, benchmarking will become a standard that can guide managers, producers, and environmental agencies on planning and aquaculture enterprise management, aiming for the development of sustainable and responsible aquaculture.

2.MATERIALS E METHODS

2.1. Study area

The study was conducted at four commercial fish farms in the São Paulo State, Brazil, being two located in the "Vale do Ribeira" Region and the other two in the Chavantes Reservoir (n=4) (Figure 1). The farms raised Nile tilapia (*Oreochromis niloticus*) in net-cages.

Figure 1. Commercial fish farms studied in the "Chavantes Reservoir" and in the "Vale do Ribeira" Region - São Paulo. A: Large-scale fish farming in Fartura – SP; B: Medium-scale fish farming in Fartura – SP; C: Small-scale fish farming in Sete Barras - SP; D: Small-scale fish farming in Juquiá – SP.

The "Vale do Ribeira" Region is located in the south of the state, in the watershed of the Ribeira de Iguape River and has large areas of well-preserved Atlantic Forest. The climate is tropical monsoon (Am, according to the Köppen climate classification). Two farms from the study are located in this region. One is located in the city of Sete Barra (Farm C), and the other in the city of Juquiá (Farm D) (Figure 2). The Chavantes Reservoir is located in the south-west of the state. This reservoir is located in the watershed of the Paranapanema River, has an area of 400 km² and a humid subtropical climate (Cfa, according to Köppen climate classification) (ROLIM *et al.*, 2007). The two other farms from the study were located in this region. Both are located in the city of Fartura (Farm A and B) (Figure 2).

Figure 2. Commercial fish farms studied in the “Chavantes Reservoir” and in the “Vale do Ribeira” Region - São Paulo. A: Large-scale fish farming in Fartura – SP; B: Medium-scale fish farming in Fartura – SP; C: Small-scale fish farming in Sete Barras - SP; D: Small-scale fish farming in Juquiá – SP.

The Environment National Council (CONAMA) Resolution 413/2009 classifies the size of the aquaculture enterprises according to its area or volume (BRASIL, 2009). The classification has three production scales. Small-scale with less than 1,000 m³, medium-scale that goes from 1,000 to 5,000 m³ and large-scale with over 5,000 m³. In this study, farm A was classified as large-scale. Farm B was classified as medium-scale, and farms C and D were classified as small-scale (Table 1).

Table 1. Characteristics of the fish farms studied in the “Chavantes Reservoir” (A and B) and in the “Vale do Ribeira” Region (C and D)- São Paulo.

Information	Unit	Farms			
		A	B	C	D
Farm size	ha	>5.0	>5.0	<5.0	<5.0
Total net-cages volume	m^3	>5,000	4,000	<1,000	<1,000

Net-cage size	m^3	54.0 (6x6x1.5)	16.2 (3x3x1.8)	4.8 (2x2x1.2)	4.8 (2x2x1.2)
Tilapia production	t/year	150	80	13	9.5
Final density	kg/m^3	42.9	37.1	41.9	43.0
Average depth	m	15.0	9.0	6.0	5.0

2.2. Sampling design

One production cycle of each farm was monitored in the field. The cycles had different lengths on each farm. They lasted for 189 days on farm A and B (October 2016 through May 2017), for 242 days on farm C (October 2016 through June 2017), and for 263 days on farm D (October 2016 through July 2017). Data were obtained on growth performance, nutritional information of commercial feed used and water parameters measured. These cycles were divided into three stages, according to the average body weight: Stage I – until 100g; Stage II – from 100g to 500g; and Stage III – over 500g. During the production cycle, three batches (sample units) were monitored in each fish farm, resulting in twelve sample units evaluated.

The data from the monitored production cycle were also used to calculate growth rate, expressed as Thermal-unit Growth Coefficient (TGC), according to Iwama and Tautz (1981). Feed samples were collected and analyzed from each farm according to the farming cycle. The information necessary to apply the ESI defined by Valenti *et al*. (2018), is shown in the flowchart (Figure 3).

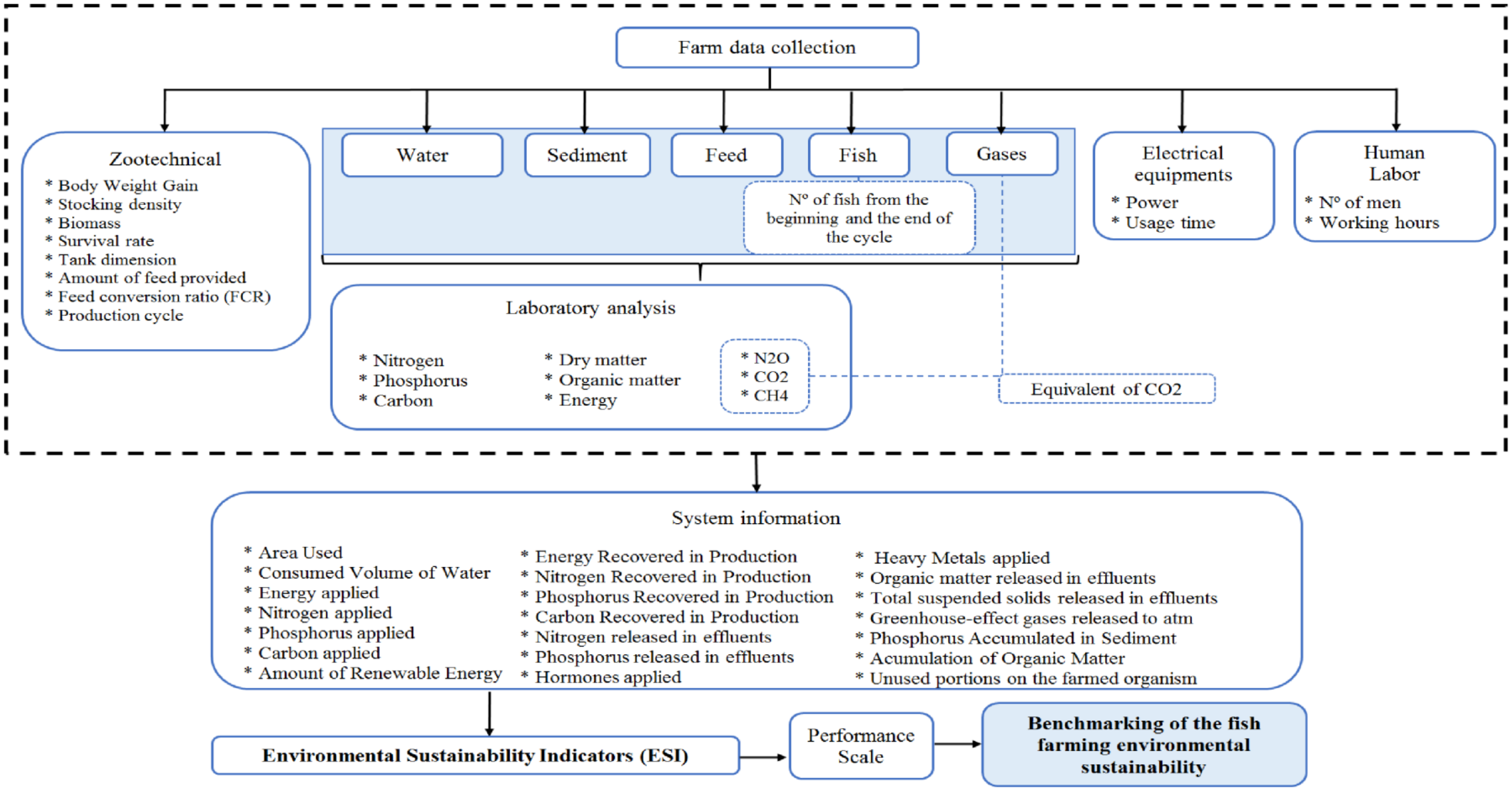


Figure 3. Flowchart representing the application of the Environmental Sustainability Indicators (ESI) by Valenti et al (2018). Source: flowchart adapted from Godoy (2019).

2.3. Water quality and feed composition

Daily, at 11 a.m., the parameters of water temperature (°C) were analyzed on the surface of the water tanks. Also, the same parameters were analyzed in an area 400m distant from the culture site, to serve as controls. Monthly, the parameters of pH, dissolved oxygen (DO), transparency and electrical conductivity (EC) were analyzed using a YSI 6820 Multi-Parameter Water Quality Sonde.

The feed samples collected from each farm were identified and preserved in thermal bags at -10ºC and, subsequently, were analyzed for dry matter (100 °C, 8 h) and ash (550 °C, 4 h), according to AOAC (1995). Crude protein was analyzed through the determination of total nitrogen by the Kjeldahl method (% nitrogen x 6.25) with a Kjeltech 1030 Autoanalyzer (Tecator, Hoganas, Sweden) (AOAC, 2000). Lipid content was determined by acid hydrolysis method following the proposed by AOAC (2000). Total phosphorus content was obtained by the colorimetric method, according to Nakamura (1957). Nitrogen-free extract (NFE) was obtained through the formula (NFE = dry matter - crude protein - lipids - ash). Gross energy (GE) was determined with a calorimeter bomb (Parr Instruments, Moline, IL, USA). A coefficient of variation of less than 5% between replicates was considered acceptable. Otherwise, the samples were analyzed again.

2.4. Growth performance and Thermal-unit Growth Coefficient (TGC)

Monthly were performed the biomass biometry of 5% of the animals of each net-cage. These data were used to calculate initial and final body weight, initial and final biomass, feed conversion ratio (FCR) and average daily gain (ADG). Body growth modeling was applied by the equation that evaluates the TGC, maintaining fixed body weight exponent (1-b = 0,3333) according to Iwama and Tautz (1981). Afterward, this exponent was calibrated by interaction according to Dumas *et al.* (2010). The least-squares method was applied to minimize the residual sum of squares (RSS), after obtaining the growth values of tilapia. Thus, the performance of the model of body growth assessment was compared by the RSS values. This comparison is a determinant factor to perform proper adjustment for the water temperature and tilapia metabolism conditions in the stages of cultivation.

$$\text{FCR} = \frac{Feed}{\Delta Biomass} \qquad \text{Eq. 1}$$

$$\text{ADG} = \frac{FBW - IBW}{d} \qquad \text{Eq. 2}$$

$$\text{TGC} = \frac{FBW^{(1-b)} - IBW^{(1-b)}}{\sum t * d} \times 100 \qquad \text{Eq. 3}$$

In which, *Feed* is the total feed provided. ∆Biomass is the difference between the final biomass and initial biomass. *FBW* and *IBW* are final and initial body weight (g), respectively. *t* is temperature (°C). *d* is day and (1-b) is the body weight exponent (DUMAS *et al*., 2010). Then, FBW was calculated by the reorganization of Equation 3, allowing adjustment of this equation:

$$\text{For TGC, } FBW(g) = \left[IBW^{(1-b)} + \frac{TGC}{100}\sum t * d\right]^{\frac{1}{(1-b)}} \qquad \text{Eq. 4}$$

This application made possible to define different TGC indices for different production scenarios of each farm, allowing the evaluation of different production systems efficiency along with other sustainability indicators evaluated.

2.5. Environmental evaluation

Samples of water, sediment, fish, feed provided and greenhouse gases were necessary to measure the environmental sustainability of each farm. These samples were collected three times throughout the production cycle of each property, representing the beginning, middle, and end of cultivation. The analyses were performed by the Sustainable Aquaculture Laboratory of CAUNESP, at the São Vicente Campus of UNESP. The data required to calculate the environmental sustainability indicators were obtained by the methods described below. These data were analyzed according to the methodology proposed by Valenti *et al*. (2018). The environmental indicators were divided into five criteria: the use of natural resources; efficiency in the use of resources; release of pollutants and unused by-products to the environment; pollutants accumulated on the bottom of the water body; and conservation of genetic diversity and biodiversity.

A. Use of the main natural resources

- Use of Space (S): used area per unit of production (Equation 1).

$$S = \frac{Area\ used\ (ha)}{Production\ (t)} \qquad Eq.1$$

- Dependence on Water (W): total volume of water used per unit of production (Equation 2). The total volume of water was estimated according to Boyd *et al*. (2007), which affirm that the only water used is that incorporated into biomass.

$$W = \frac{Consumed\ volume\ (m^3)}{Production\ (t)} \qquad Eq.2$$

- Use of Energy (E): total energy applied to the system per unit of production (Equation 3).

$$E = \frac{Energy\ applied\ (MJ)}{Production\ (t)} \qquad Eq.3$$

- Proportion of Renewable Energy (PRE): amount of renewable energy used per total amount of applied energy (Equation 4). Renewable energy sources include food, organic fertilizer, ethanol, biodiesel and other energy obtained from live organisms, and solar (photovoltaic), wind, tidal and geothermal energy. Hydropower is not considered renewable because water reservoirs have a limited life span.

$$PRE = \frac{Amount\ of\ renewable\ energy\ (MJ)}{Total\ amount\ of\ applied\ energy\ (MJ)} \qquad Eq.4$$

- Use of Nitrogen (N): mass of nitrogen applied in the system per unit of production (Equation 5). The mass of nitrogen applied is the amount of nitrogen contained in the feed offered and animals stocked.

$$N = \frac{Mass\ of\ nitrogen\ applied\ (kg)}{Production\ (t)} \qquad Eq.5$$

- Use of Phosphorus (P): mass of phosphorus applied in the system per unit of production (Equation 6). The mass of phosphorus applied is the amount of phosphorus contained in the feed offered and animals stocked.

$$P = \frac{Mass\ of\ phosphorus\ applied\ (kg)}{Production\ (t)} \quad Eq. 6$$

- Use of Carbon (C): mass of carbon applied in the system per unit of production (Equation 7). The mass of carbon applied is the amount of carbon contained in the feed offered and animals stocked. This indicator was added according to Proença (2013).

$$C = \frac{Mass\ of\ carbon\ applied\ (kg)}{Production\ (t)} \quad Eq. 7$$

B. Efficiency in using resources

- Efficiency in the Use of Energy (EE): the energy recovered in production per the energy applied (Equation 8). The energy recovered in production is the average energy content of the harvested fish multiplied by production.

$$EE = \frac{Energy\ recovered\ in\ production\ (MJ) \times 100}{Total\ amount\ of\ energy\ applied\ (MJ)} \quad Eq. 8$$

- Efficiency in the Use of Nitrogen (EN): amount of nitrogen incorporated in production per amount of nitrogen applied (Equation 9). The amount of nitrogen incorporated is the average nitrogen content of the harvested fish multiplied by production.

$$EN = \frac{Mass\ of\ nitrogen\ recovered\ in\ production\ (kg) \times 100}{Mass\ of\ nitrogen\ applied\ (kg)} \quad Eq. 9$$

- Efficiency in the Use of Phosphorus (EP): amount of phosphorus incorporated in production per amount of phosphorus applied (Equation 10). The amount of phosphorus incorporated is the average phosphorus content of the harvested fish multiplied by production.

$$EP = \frac{Mass\ of\ phosphorus\ recovered\ in\ production\ (kg) \times 100}{Mass\ of\ phosphorus\ applied\ (kg)} \quad Eq. 10$$

- Efficiency in the Use of Carbon (EC): amount of carbon incorporated in production per amount of carbon applied (Equation 11). The amount of carbon incorporated is the average carbon content of the harvested fish multiplied by production. This indicator was added according to Proença (2013).

$$EC = \frac{Mass\ of\ carbon\ recovered\ in\ production\ (kg) \times 100}{Mass\ of\ carbon\ applied\ (kg)} \quad Eq. 11$$

- Production Actually Used (PU): proportion of unused wastes of the farmed organism per unit of production (Equation 12). In this study, the fish were sold as whole fish, so it was calculated that 100% was used.

$$PU = \frac{Mass\ of\ unused\ portions\ of\ the\ farmed\ organism \times 100}{Production\ (kg)} \quad Eq. 12$$

C. Pollutants released to the environment

- Potential of Phosphorus Eutrophication (PEp): mass of phosphorus released in effluent per unit of production (Equation 13). Mass of phosphorus released was calculated by the difference between the amount contained in the feed offered and the phosphorus recovered in the final biomass produced summed with the load of phosphorus accumulated in sediment.

$$PEp = \frac{Mass\ of\ phosphorus\ released\ in\ effluent\ (kg)}{Production\ (t)} \quad Eq. 13$$

- Potential of Nitrogen Eutrophication (PEn): mass of nitrogen released in effluent per unit of production (Equation 14). Mass of nitrogen released was calculated by the difference between the amount contained in the feed offered and the nitrogen recovered in the final biomass produced.

$$PEn = \frac{Mass\ of\ nitrogen\ released\ in\ effluent\ (kg)}{Production\ (t)} \quad Eq. 14$$

- Potential of Organic Pollution (POP): mass of organic matter released in effluent per unit of production (Equation 15). Mass of organic matter released was calculated by the difference between the amount contained in the feed offered and the organic matter recovered in the final biomass produced summed with the load of organic matter accumulated in sediment.

$$POP = \frac{Mass\ of\ organic\ matter\ released\ in\ effluent\ (kg)}{Production\ (t)} \quad Eq. 15$$

- Potential of Global Warming (PGW): sum of the mass of gases released to the atmosphere and absorbed by cages per unit of production (Equation 16). The mass of gases was calculated using the emission and absorbed mass of N_2O + CO_2 + CH_4 (measured in equivalents of CO_2) according to IPCC guidelines (IPCC, 2008).

$$PGW = \frac{Load\ of\ greenhouse - effect\ gases\ released\ to\ the\ atmosphere\ (kg)}{Production\ (t)} \quad Eq. 16$$

- General Chemical Pollution (GCP): load of applied chemical products per unit of production (Equation 17). Load of applied chemical products is the sum of herbicides, insecticides, anti-algals, antibiotics, and other chemicals applied. In this study, it is suggested to develop a multiplying factor related to the impact of each chemical. In the farms studied, they used antibiotics and the amount was multiplied by factor 20. This factor was arbitrarily set.

$$GCP = \frac{Load\ of\ applied\ chemical\ products\ (kg)}{Production\ (t)} \quad Eq. 17$$

- Pollution by Hormones (PH): amount of hormones applied per unit of production (Equation 18).

$$PH = \frac{Mass\ of\ hormones\ applied\ (kg)}{Production\ (t)} \quad Eq. 18$$

- Pollution by Heavy Metals (PHM): amount of heavy metals applied per unit of production (Equation 19).

$$PHM = \frac{Mass\ of\ heavy\ metals\ applied\ (kg)}{Production\ (t)} \quad Eq. 19$$

D. Pollutants accumulated on the bottom of the water body

- Accumulation of Phosphorus (AP): amount of phosphorus in the sediment generated per unit of production (Equation 20). Amount of phosphorus is calculated through the amount of phosphorus on the sample per area multiplied by the area of the cage.

$$AP = \frac{Load\ of\ P\ accumulated\ in\ sediment\ (kg)}{Production\ (t)} \quad Eq. 20$$

- Accumulation of Organic Matter (AOM): amount of organic matter in the sediment generated per unit of production (Equation 21). Amount of organic matter is calculated through the amount of organic matter on the sample per area multiplied by the area of the cage.

$$AOM = \frac{Load\ of\ organic\ matter\ accumulated\ in\ sediment\ (kg)}{Production\ (t)} \quad Eq. 21$$

E. Risk of the farm to the conservation of genetics and biodiversity

- Risk of Farmed Species (RFS): scores = {1, 2, 3, 4, 5, 6 or 8}.

1=Local strain farmed in an open or closed system;
2=Species within the same basin (but not local strain) farmed in a closed system;
3=Species within the same basin farmed in an open system;
4=Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in a closed system;
5=Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in an open system;
6=Transgenic variety of any species farmed in a closed system;
8=Transgenic variety of any species farmed in an open system.

2.5.1. Water analyses

Samples of reservoir water were collected to determine total carbon, total nitrogen, and total phosphorus contents. Carbon content was determined by combustion catalytic oxidation using a Vario TOC Select (Elementar®). Nitrogen content was determined according to the persulfate method (APHA, 2005; 4500-N C.). To determine phosphorus content, samples were submitted to previous digestion so that the compounds associated with the organic matter were released as orthophosphate, according to the persulfate digestion method (APHA, 2005 - method 4500-P B5). After that, orthophosphate was measured by the stannous chloride method (APHA, 2005; method 4500-P D), using a spectrophotometer (Shimadzu UV 1800®).

2.5.2. Sediment analyses

This method was adapted from Moura *et al.* (2016). Sediment samples were collected to determine dry weight and content of total carbon and total phosphorus. Sediment generated was measured with the installation of tripton samplers below the cages for 24 hours. Additional chambers were installed in an area 400m distant from the culture site, to serve as a control for natural sedimentation in the reservoir. After this period, tripton samplers were removed and the collected material was preserved cooled in ice and taken for analysis. The dry matter was determined by drying the samples at 95-100°C as described in AOAC (1995, method 934.01). The carbon content was determined by high-temperature combustion in a CHNS Elemental Analyzer (Vario Macro Cube - Elementar®). In the combustion process, the samples were converted to gas and detected by a TCD detector (Thermal Conductivity Detector). The phosphorus content was determined according to the metavanadate colorimetric method, applied to samples previously incinerated in a muffle for 4 hours at 550°C (MICHELSEN, 1957).

2.5.3. Gases analyses

Emission of carbon and nitrogen into the atmosphere can occur by bubbles and diffusive gas exchange at the water-air interface (MATVIENKO *et al.*, 2001). To catch the bubbles, fiberglass funnels suspended by floats were installed on net cages surface at the beginning and the end of the fattening period (over 500g). The funnel mouth diameter was 36cm and the height was 35cm. In the tip was fastened a graduated tube (250 ml) where the bubbles were accumulated over a 24-h period. After this period, the tubes were taken to the laboratory for chromatographic analysis. The diffusion at the water-air interface was evaluated at the beginning and the end of the culture using the equilibration method. With diffusion chambers, confined portions of air were allowed to partially equilibrate with the gas dissolved in the water, over 0-, 1-, 2- and 4-min periods. Then, these portions of air were conditioned in transfer tubes for later gas chromatographic analysis (Construmaq, São Carlos-SP). The amount of N_2O, N_2, CO_2, and CH_4 was determined using gas chromatography (Shimadzu GC-2014®), with TCD (Thermal Conductivity Detector), FID (Flame Ionization Detector) and ECD detectors (Electron Capture Detector). The methods are described in Matvienko *et al.* (2001). The final value corresponds to the sum of absorption or emission during daytime and at nighttime throughout the experiment.

2.5.4. Fish carcass analyses

The fish collected samples (stocked and harvested) were used to determine the average biomass and total carbon, total nitrogen, and total phosphorus contents. They were analyzed in triplicate (AOAC, 1995; 969.31 A) and the mean concentrations were multiplied by the total biomass of animals. For this, the samples were kept in an oven (Nova Ética, 400-6ND-200C) at 60ºC for 48 h. Afterward, they were weighed, ground and sent for analysis. Carbon, nitrogen, and phosphorus were analyzed according to the methods described in section 2.5.2. Nitrogen content was determined by the analysis described in APHA (2005; 4005-Norg).

2.6. Statistical analyses

2.6.1. Performance scale expressed in multidimensional diagrams (Environmental Sustainability Index)

This methodology was adapted from Proença (2013), where each indicator was converted into a performance scale, with scores ranging from 0 to 100. The treatment with the best indicator value (more sustainable when compared to the others) was arbitrarily scored as 100, and the others were determined by proportion. Thus, the indicators were grouped into 5 categories: (a) Use of resources; (b) Efficiency of resources; (c) Pollutants released; (d) Pollutants accumulated; (e) Biodiversity. An environmental sustainability sub-index was computed for each category by the average of their respective indicators. They were expressed in multidimensional diagrams. Only the category (e) represents the value of its unique indicator. The Environmental Sustainability Index was determined by the average of the 5 sub-indicators.

2.6.2. Development of environmental sustainability benchmarking

Data of ESI obtained from each evaluated farm and the literature review (n= 10) were used to develop a "standard" value for the Nile tilapia cage culture system, by the average of the indicators. The data selected from the literature review were the ones that used the same methods to evaluate the ESI. To realize the application of the environmental sustainability benchmarking, it was used the ESI obtained for the farms on this study and compared with the "standard" value.

$$\text{Benchmarking} = \frac{Data\ observed}{\text{"}Standard\text{" } value} x100$$

To interpret the result obtained, it was necessary to observe the category that was analyzed. In the categories "Use of the main natural resources", "Pollutants released to the environment", and "Pollutants accumulated on the bottom of the water body", a result over 100% means worse performance compared to the "standard". In the category "Efficiency in using resources", a result over 100% means better performance compared to the "standard".

3.RESULTS

3.1. Quality of water and feed

Water quality was analyzed individually where each farm had its control site for comparison using statistical analysis. Each farm maintained water quality values in the tanks close to their respective controls (Table 2), except for DO that showed a significant difference ($P<0.05$) for farms A and C, and pH for farm A. The average for water temperature on farms A, B, C, and D were 27.1°C, 27.0°C, 25.0°C, and 26.1°C, respectively. The pH remained between 5.9 and 7.3 and the EC obtained a minimum of 26.53 $\mu S.cm^{-1}$ and a maximum of 56.81 $\mu S.cm^{-1}$.

During the production cycle, three commercial feed were used in each farm according to the fish weight. 4mm pellets, from 30 to 100g body weight; 6mm pellets, from 100 to 500g body weight; and 8mm pellets, over 500g body weight. The averages composition of each feed analyzed are shown in Table 3.

Table 2. Average (±SD) values of water quality during the production of Nile tilapia (*Oreochromis niloticus*) at 4 fish farms in the state of São Paulo – Brazil, located in the Chavantes Reservoir (A and B) and the "Vale do Ribeira" Region (C and D).

Farms	A			B			C			D		
	C	Tk	P value	C	Tk	P value	C	Tk	P value	C	Tk	P value
D.O. (mg L^{-1})	6.0±1.4	2.9±1.1	<0.0001*	6.4±2.5	4.3±2.7	0.069	4.5±1.5	1.2±0.3	0.005*	5.3±3.2	3.9±2.6	0.245
pH	7.7±0.6	7.3±0.3	0.026*	7.1±0.3	7.0±0.2	0.222	5.9±0.3	5.9±0.4	0.717	7.0±0.6	7.1±0.4	0.536
EC. (µS cm^{-1})	41.25±2.99	41.93±3.01	0.587	56.18±6.02	56.81±5.14	0.784	26.30±10.30	26.53±10.92	0.959	51.60±17.54	51.60±17.69	0.999

C, control; Tk, tank; D.O., dissolved oxygen; EC., electrical conductivity; *, when P<0.05, there was a significant difference between control and tank, by ANOVA.

Table 3. Averages (±SD) composition of feed used in the commercial production of Nile tilapia by weight range.

Parameter	Unit	4mm				6mm				8mm			
		A	B	C	D	A	B	C	D	A	B	C	D
Feed provided	kg	350.0±0.0	356.7± 20.8	33.0±8.9	46.0±3.6	1571.7± 132.3	1276.7± 73.7	173.7± 38.8	208.3± 38.8	1998.3± 296.1	1280.0± 105.8	130.0± 17.3	218.0± 72.0
Dry matter	%	91.4±0.1	92.7±0.2	90.1±0.2	89.8±0.1	89.6±0.2	93.0±0.1	91.6±0.5	92.4±0.2	92.6±0.1	92.1±0.1	92.0±0.2	90.2±0.3
Gross energy	MJ kg^{-1}	18.1±0.1	18.0±0.0	19.4±0.1	18.9±0.1	18.6±0.3	17.9±0.0	16.9±0.0	18.8±0.1	18.5±0.3	19.1±0.0	16.4±0.1	18.8±0.1
Crude protein	%	30.4±3.8	30.1±1.5	39.5±0.5	29.2±1.0	32.3±1.3	29.9±0.5	22.3±2.1	28.9±1.5	30.6±1.4	33.3±0.6	21.6±0.4	28.3±0.8
Phosphorus	%	1.3±0.0	1.2±0.0	1.4±0.0	1.1±0.0	1.2±0.0	1.2±0.0	0.8±0.0	1.3±0.0	1.1±0.0	1.1±0.0	0.6±0.0	1.3±0.0
Carbon	%	41.8±0.8	40.8±0.8	42.7±0.0	42.1±0.2	42.8±1.5	41.8±1.8	38.8±1.5	41.3±0.7	40.8±1.2	46.2±0.7	39.7±1.5	41.6±0.3

4mm (30 to 100g); 6mm (100 to 500g); 8mm (> 500g).

3.2. TGC and production data

The farms that showed better growth performance had a higher average temperature (Table 4). The days of cultivation from farms A and B were shorter and both achieved the highest ADG (g) (4.8 and 4.6 respectively). Farm D had an FCR about 5% more efficient than the average of other farms.

Table 4. Growth performance and Thermal-unit Growth Coefficient (TGC) of the Nile tilapia cage farming at 4 fish farms in the state of São Paulo – Brazil.

Farms	A	B	C	D
TGC	0.0147	0.0148	0.0105	0.0108
Average Temp. (°C)	27.1	27.0	25.0	26.1
Days of production	189	189	242	263
IBW (kg)	0.010	0.008	0.005	0.010
FBW(kg)	0.912	0.872	0.583	0.855
Initial Biomass (kg)	31.7	20.0	2.2	4.8
Final Biomass (kg)	2318.5	1743.4	201.3	297.3
FCR	1.71	1.69	1.69	1.62
Feeding Rate (%)				
4mm	22.1	35.7	27.2	17.0
6mm	8.4	8.1	6.9	5.4
8mm	2.1	1.7	1.3	1.5
ADG (g)	4.8	4.6	2.4	3.2

TGC, thermal-unit growth coefficient; IBW, initial bodyweight; FBW, final bodyweight; FCR, feed conversion ratio; 4mm (30 to 100g); 6mm (100 to 500g); 8mm (> 500g); ADG, average daily gain. A: Large-scale fish farming in Fartura – SP; B: Medium-scale fish farming in Fartura – SP; C: Small-scale fish farming in Sete Barras - SP; D: Small-scale fish farming in Juquiá – SP.

3.3. Environmental Sustainability Indicators

3.3.1. Use of natural resources

Farm C showed 17% less use of energy, nitrogen, phosphorus, and carbon than the other farms, on average (Table 5). Farm B used at least 64% less space per unit of production than any other farm, but this indicator showed low levels in all farms. None of the farms used renewable energy.

3.3.2. Efficiency in the use of natural resources

Farm C showed the highest efficiency in the use of nitrogen and phosphorus (32.7% and 23.6%, respectively). Efficiency in the use of phosphorus at Farm B was the lowest, less than half of the efficiency from farm C. However it was the most effective treatment for energy. All treatments had the same efficiency for the production actually used and had similar results for energy efficiency use (Table 5).

3.3.3. Pollutants released to the environment and accumulated on the bottom of the water body

Farm C and D released less phosphorus and nitrogen to the environment, with the difference between them of less than 2kg/t. Farm B released an amount of phosphorus two times higher than farm C and D. Farm A released more nitrogen and organic pollution (67 and 1,096 kg/t, respectively), but it was the only one that absorbed greenhouse gases (Table 5). Accumulations of phosphorus and of organic matter were the lowest in farm B and the highest in Farm D, with levels 10 and 8 times higher for phosphorus and organic matter, respectively (Table 5).

3.3.4. Risk of farmed species

All farms received the value 4 for risk of famed species - Allochthonous species, native species with reduced genetic variability, or hybrid (native or allochthonous species) farmed in a closed system.

Table 5. Environmental sustainability indicators of Nile tilapia cage farming

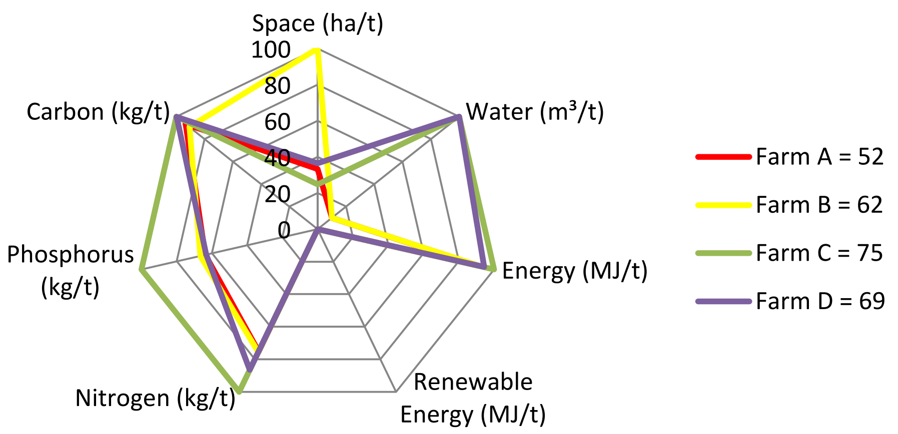
Indicator	Farm			
	A	B	C	D
1- Use of the main natural resources				
Use of Space (ha/t)	0.0016	0.0005	0.0021	0.0014
Dependence on Water (m^3/t)	0.75	0.75	0.08	0.08
Use of Energy (MJ/t)	31,637	31,303	28,754	30,491
Proportion of Renewable Energy (MJ/t)	0	0	0	0
Use of Nitrogen (kg/t)	86	85	64	75
Use of Phosphorus (kg/t)	20	19	13	21
Use of Carbon (kg/t)*	718	739	670	673
2- Efficiency in using resources				
Efficiency in the Use of Energy (%)	22.1	23.8	21.9	22.0
Efficiency in the Use of Nitrogen (%)	22.2	27.0	32.7	21.4
Efficiency in the Use of Phosphorus (%)	16.1	11.4	23.6	16.4
Production Actually Used (%)	100	100	100	100
3- Pollutants released to the environment				
Potential of Phosphorus Eutrophication (kg/t)	14	16	7	7
Potential of Nitrogen Eutrophication (kg/t)	67	61	54	56
Potential of Organic Pollution (kg/t)	1,096	1,079	1,005	407
Potential of Global Warming (kg/t)	-204	114	363	93
General Chemical Pollution (kg/t)	1.5	1.1	1.2	0.9
Pollution by Hormones (kg/t)	0	0	0	0
Pollution by Heavy Metals (kg/t)	0	0	0	0
4- Pollutants accumulated on the bottom of the water body				
Accumulation of Phosphorus (kg/t)	4	1	3	10
Accumulation of Organic Matter (kg/t)	96	90	129	723
5- Risk of the farm to the conservation of genetics and biodiversity				
Risk of Farmed Species (RFS)	4	4	4	4

3.4. Environmental sustainability index

On the category use of resources and efficiency in using resources, farm C was more efficient. Farm B showed the best performance on pollutants accumulated, with differences from 29 to 87 points from the other farms. Farm D released fewer pollutants to the environment (86), however, it accumulated more pollutants on the bottom of the water body (13), in relation to the other farms.

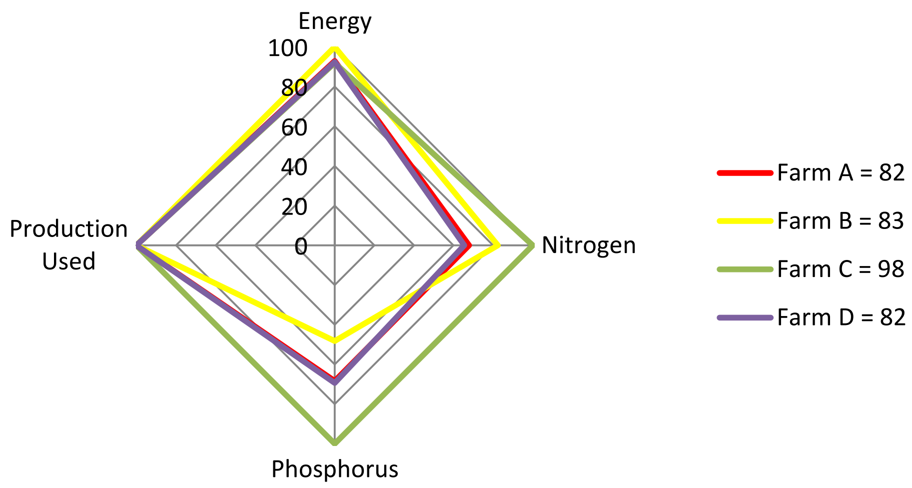
Use of Resources

a.



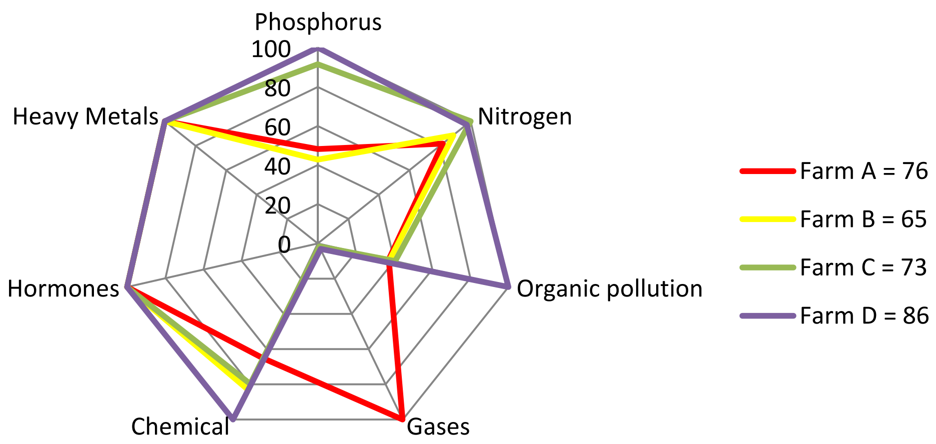
Efficiency in using resources

b.



Pollutants released

c.



d.

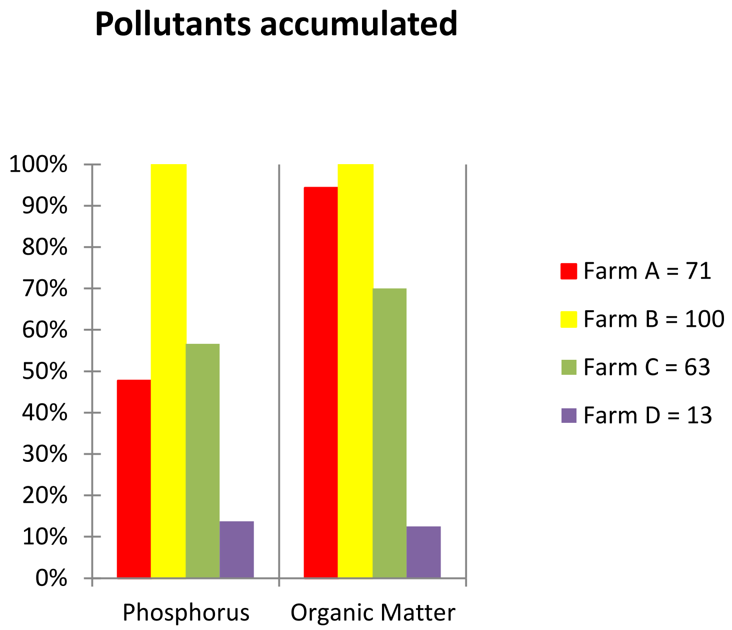


Figure 4. Indicators of sustainability obtained for each category: a. Use of the main natural resources; b. Efficiency in using resources; c. Pollutants released to the environment; d. Pollutants accumulated on the bottom of the water body. The respective sub-index for each treatment is shown beside the graphic.

The results of each category of the set of environmental indicators (sub-index) were considered to calculate the final environmental sustainability index (Table 6). The largest difference was observed in pollutants accumulated, with 87 points of difference from the first to the last. The Final Score points out that farms B and C were the most environmentally sustainable. Farm D was the least one.

Table 6. Environmental Sustainability Index for each farm. The final score is the average of all sub-index.

Sub-index	FARM			
	A	B	C	D
Use of Resource	52	62	75	69
Efficiency	82	83	98	82
Pollutants released	76	65	73	86
Pollutants accumulated	71	100	63	13
Biodiversity	100	100	100	100
Final Score	**76**	**82**	**82**	**70**

3.5. Environmental sustainability benchmarking

Averages of a group of ESI were obtained from the data of this study and from a literature review (Table 7). There are few publications on ESI for Nile tilapia raised in cage or net-pen (BOYD *et al.*, 2007; ALMEIDA, 2013; MOURA *et al.*, 2016). In the criteria 1, 3 and 4 (use of the main natural resources, pollutants released to the environment, and pollutants accumulated on the bottom of the water body, respectively), a higher percentage means worse performance compared to the average. In the criterion 2 (efficiency in using resources), a higher percentage means better performance.

Table 7. Average (±SD) of a data set from environmental sustainability indicators of Nile tilapia cage farming.

Indicator	Data and Literature Average	*Farms			
		A	B	C	D
1- Use of the main natural resources**					
Use of Energy (MJ/t)	44,041± 30,196	72%	71%	65%	69%
Use of Nitrogen (kg/t)	80±9	107%	107%	81%	93%
Use of Phosphorus (kg/t)	17±4	121%	116%	77%	122%
Use of Carbon (kg/t)	678±95	106%	109%	99%	99%
2- Efficiency in using resources***					
Efficiency on the Use of Energy (%)	22.5±0.9	98%	106%	98%	98%
Efficiency on the Use of Nitrogen (%)	24.4±4.2	91%	110%	134%	88%
Efficiency on the Use of Phosphorus (%)	21.2±9.4	76%	54%	111%	77%
3- Pollutants released to the environment**					
Potential of Phosphorus Eutrophication (kg/t)	10±4	137%	154%	72%	66%
Potential of Nitrogen Eutrophication (kg/t)	61±5	110%	101%	90%	92%
Potential of Organic Pollution (kg/t)	848±305	129%	127%	118%	48%
4- Pollutants accumulated on the bottom of the water body**					
Acumulation of Phosphorus (kg/t)	4±4	82%	39%	69%	285%
Acumulation of Organic Matter (kg/t)	221±281	43%	41%	58%	327%

* The calculation was the relation between the indicators values obtained for farms A to D on table 5 and the averages.
** Criteria 1, 3 and 4: >100%, worse performance compared to the average.
*** Criteria 2: >100%, better performance compared to the average.

4. DISCUSSION

4.1. Quality of water and feed

The average temperature from farms A and B, that are located in the Chavantes Reservoir, were higher than average from farms C and D, which are located on the “Vale do Ribeira” Region. This is expected due to the first region to be warmer than the second (ROLIM *et al.*, 2007). Also, all the temperatures stayed in a tolerable limit for tropical fish species, that is, between 24 to 30°C (BOYD AND TUCKER, 1998).

Although the highest DO concentration in the tank was observed at Farm B, all farms showed values under 5.0 mg L^{-1}, which is the minimum limit established by CONAMA Resolution N. 357/2005 for Class II water bodies. One of the main reasons for these low values of DO can be related to the indirect effect of cloudiness that was observed during the sampling on farms A, C, and D that was not observed on farm B (FAST & LASTER, 1992).

All average values for EC kept similar values in each farm between the control and tank (Table 2). The conductivity values observed in all farms did not indicate impacted environments. An indication that the environment is impacted is when values of conductivity are above 100 µS cm^{-1} (CETESB, 2009). Also, pH values stayed in the recommended levels (from 6.0 to 9.0), according to CONAMA Resolution 357 for water used for aquaculture (2005) and Boyd *et al* (2003). These levels of pH contribute to good development for fish farming and do not affect ecosystem water quality (BUENO *et al*, 2008).

The average composition of feed from each farm had similar values. The exception is for Farm C that had the lowest levels of gross energy, crude protein, phosphorus, and carbon, on 6mm and 8mm commercial feeds. These information are essential to understand one of the reasons for the worst growth performance (farm C) (lowest TGC and ADG, Table 4).

The levels of crude protein (CP) used for farm C was 21.6%, in the 8mm feed, that is, fish over 500g. This level is lower than the requirements for tilapia raised in net-cages in this stage of life, which demands levels between 28 to 32%

(WATANABE *et al.,* 1997; COSTA *et al.,* 2009). Diets with lower levels of protein decrease nitrogen excretion (FURUYA *et al*., 2005), which was observed in farm C that showed the best efficiency in using resources (Table 5, Figure 4), but these diets demand a supplementation of amino acids to achieve the same fish growth performance. In the scenario of farm C, this loss in performance indicates a need to change the 8mm feed, so that it can keep the efficiency in using resources but also achieve a better growth performance.

4.2. Growth Performance (TGC)

There is a considerable difference between the performances from the farms when we compare the two different regions, mainly due to the climate of each region. When comparing farm A with B and C with D, we have more similar results. The farms from the same region (A and B) achieved the highest's TGC. One of the main reasons is the average temperature that was higher when compared to the farms from the other region (C and D). As fish are ectotherms, the higher water temperature can result in increased feed intake and fish growth (HOULIHAN *et al*., 2001). Farms A and B had the shortest cultivation time (189 days), with the highest ADG (average of 4.7g).

4.3. Environmental Sustainability Indicators

Indicators provided single information on each aspect. The interpretation of it requires to look at the numbers and to comprehend the reasons for the value found of the environmental concern (PROENÇA, 2013).

4.3.1. Use of natural resources

Net cage culture in reservoirs is very efficient in the use of space. It uses the least area, over more than two orders of magnitude, when compared to others aquaculture systems (ALMEIDA, 2017; BOYD *et al.*, 2007; COSTA, 2019; ISLAM, 2002; GILSON, 2019; GONÇALVES, 2017; PEREIRA, 2019; PROENÇA, 2013). The results obtained for the use of space were low on every farm. Farm C showed the highest number (0.0021 ha/t), but this indicator stills many times lower than other systems, e.g. Lambari aquaculture (land-based system) that uses from 1.2 to 1.6 ha/t (ALMEIDA, 2017).

When compared to land-based cultures, the dependence on water for cultures in reservoirs is lower. Boyd *et al.* (2007) state that cage and net-pen culture use the least water (0.75m³/t). They affirm that the only water consumed is that incorporated into biomass. For this indicator (Dependence on Water), all farms used less than 1 m³ per unit of production. This indicator points out a greater advantage of cage cultures in reservoirs when compared to other cultures. Proença (2013) evaluated an integrated multi-trophic aquaculture (IMTA) system, with tilapia and prawn, raised in earthen ponds. The ponds' inflow water was just to compensate water losses by seepage and evaporation, which is a good management that reduces the volume of water used. They used an average of 7,216 m³/t, thousands of times more water than the farms evaluated in this study.

Most of the total energy, nitrogen, phosphorus and carbon applied to the system came from the feed. Farm C showed less use of energy, nitrogen, phosphorus, and carbon because the 6mm and 8mm feed had the lowest levels of these components. In tilapia culture, the average use of nitrogen and phosphorus per tonne is 86 kg and 18 kg, respectively (BOYD *et al.*, 2007). Despite farm C had around 25% less use of these indicators averages, the low levels of these components in the feed directly affected the growth performance. As discussed before in item 4.1., these lower levels improve the environmental sustainability but require some supplementations on the feed, such as supplementation of amino acids, to reach a balanced diet and avoid affecting growth performance (FURUYA *et al*., 2005).

4.3.2. Efficiency in using resources

All farms achieved efficiency in using nitrogen in the range of the expected, i.e. 22.5% according to Boyd *et al.* (2007). Farm B and C achieved even greater results due to the higher levels of nitrogen in the harvested fish carcass (8.8 and 8.2%, respectively, against 7.3% from farms A and D). The efficiency for use of phosphorus did not achieve more than 23.6% in any of the farms, which is about half of the expected (40% of efficiency; BOYD *et al.*, 2007). Comparing with the results described by Boyd *et al.* (2007), their feed had similar values for phosphorus content and FCR (1% and 1.8, respectively) in relation to the feeds used in all farms (~1.1-1.3% and 1.6-1.7). The main difference is on the level of phosphorus in the harvested fish carcass, where their results showed 28.3 g/kg (dry matter basis) compared to 13.1 g/kg (dry matter basis) from farm D that was the highest level observed between all four farms. Although, Moura *et al.* (2016) and Almeida (2013) also evaluated the sustainability of tilapia net-cage production system in reservoir, and they observed similar values for the efficiency for use of phosphorus (17.0 and 24.0%, respectively). The harvested fish carcass from farm B had the lowest level of phosphorus (8.5 g/kg in dry matter weight basis; 32% less than other farms) and this resulted in the lowest efficiency in the use of phosphorus.

The performances for use of energy in all farms were similar, and consequently, their efficiency in the use of energy had also approximated values. All farms achieved the best performance for the production actually used, because in this study, the fish were sold as whole fish, so it was calculated that 100% was used.

4.3.3. Pollutants released to the environment and accumulated on the bottom of the water body

The potential of phosphorus eutrophication was lower in farms C and D. However, the reasons for these results among them were different. Farm C was due to the lower use of phosphorus (low levels on feed), and the best efficiency in using this resource. This corroborates with Hardy and Gatlin (2002) that also reduced dietary phosphorus and had a reduction of more than 50% of fecal and urinary losses of phosphorus. Farm D is related to its accumulation of phosphorus, that reduced the phosphorus released to the environment, once that to calculate the amount released, the load of phosphorus accumulated in sediment was subtracted. The potential of nitrogen eutrophication was also lower in farms C and D and it was directly related to the lower levels of nitrogen on feed compared to farms A and B.

Boyd *et al.* (2007) state that what fish biomass does not convert from feed nutrients and organic matter, goes directly from cages into surrounding waters. The inefficiency in the use of phosphorus by farm B was the main reason for it to achieve the highest potential of phosphorus eutrophication. Farm A released more nitrogen and organic pollution because of the higher levels of these components on feed and the lower efficiency in use, i.e. less percentage on the harvested biomass. However, farm A absorbed the greenhouse gases N_2O and CH_4 through diffusion in the water-air interface. These gases are 298 and 25 times, respectively, more warming than CO_2 (IPCC, 2008). This absorption by diffusion caused the reduction of the CO_2 equivalents.

The longer days of cultivation had a direct impact on the accumulation of phosphorus and organic matter in farm D. Concomitantly, the sediment collected in this farm had a volume 4 to 7 times higher than the other farms. The main influence that cage culture has on pollutant accumulation is related to the feed used and the feeding practices, as they have direct hydrological connections to effluent-receiving water bodies and effluent treatment is almost impossible in this culture (BOYD *et al.*, 2007). Ballester-Moltó *et al.* (2017), estimated the fraction of uneaten feed from the feed supplied in fish being reared under intensive cage farming conditions, and the estimated wasted feed ranged between 8.52 and 52.20%. However, the sediment collected in a control site in farm D also showed average volumes 1.7 to 17.3 times higher than the control site from the other farms. There are factors other than aquaculture that increases pollutant accumulation. One example of a phenomenon that affects is the erosion of river banks in rainy seasons that results in increased water turbidity (CETESB, 2009). The climate of the “Vale do Ribeira” region experiences abundant rainfall in the summer season when the sediment collected for farm D showed the highest volumes. Another possibility for the higher level of pollutant accumulation is related to mining, that can impact the water quality of rivers and reservoirs due to the turbidity caused by fine sediments in suspension, as well as the pollution caused by leachate and carried substances or contained in the effluents of the mining areas, such as oils, grease, heavy metals (MECHI & SANCHES, 2010). The “Vale do Ribeira” region is a mineral production center that has densification of areas impacted by mineral extraction (FIGUEIREDO *et al.*, 2007; MECHI & SANCHES, 2010).

4.3.4. Risked of farmed species

All farms received value 4 for the indicator risk of farmed species as Nile tilapia is classified as an allochthonous species in Brazil and, in all farms studied, they were raised in a closed system. Escapes from allochthonous species can lead to negative interaction with wild populations through competition, disease and pathogen transfer and crossbreeding (JENSEN *et al*., 2010). When the system is closed reducing the possibility of animal escaping, the risk of raising allochthonous species is decreased (PROENÇA, 2013).

4.4. Environmental Sustainability Index

The environmental sustainability index allows a more effective way to compare different treatments and/or systems, through the aggregation of the indicators into a single value (PROENÇA, 2013). This allows having an easier visualization of the main positive or negative aspects of the production and points to the main factors that are affecting it.

The best score index for use of resources and efficiency in using resources was from farm C. The index pointed to a lower use of water, energy, nitrogen, phosphorus, and carbon, and higher efficiency in the use of nitrogen and phosphorus. It means that the levels and quality of the ingredients in the feed may improve environmental sustainability. However, as discussed on item 4.3.1., it's necessary to balance the diets to achieve the requirement of fish, achieving a desired performance in the environmental aspect and also in the growth performance.

Farm B had the best score index for pollutants accumulated and the worst for pollutants released. The farm accumulated less phosphorus and organic matter on the bottom and consequently increased the release of these pollutants. The higher levels of phosphorus, organic pollution, and gases released to the environment affected negatively the index pollutants released. Farm D had the opposite performance from farm B, in the index pollutants accumulated and released (worst and best, respectively). This was due to the higher accumulation of phosphorus and organic matter, and due to the lower release of phosphorus, organic pollution, chemicals and also nitrogen.

The most environmentally sustainable farms were farms B and C, according to the final environmental sustainability index. Farm C had the best performance in the categories' use of resources and efficiency in using resources. The best performance of farm B is due to the category pollutants accumulated. It was crucial to classify farm B as the most environmentally sustainable. This sub-index had the largest difference compared to the other farm, with 29 points more than the second one (farm A). Farm D was classified as the least environmentally sustainable. This is mainly due to the sub-index pollutants accumulated. The difference between farm D to the others in this category ranged from 50 to 87 points. It was not possible to find any pattern between the environmental sustainability of the farms and their production scales. Farm C (small-scale) had the best performance, while farm D, also small-scale, had the worst. Farm B (medium-scale) also had the best performance and farm A (large-scale) stayed 6 points from the best and the worst performances. This absence in a pattern shows an interesting fact, once that in most types of aquaculture production, large-scale farms expect to be less environmentally sustainable compared to smaller-scales. This environmental sustainability index helped, in an easier way, to realize a holistic interpretation of the treatments, pointing out the main propitious and limiting factors for environmental sustainability on each farm.

4.5. Environmental Sustainability Benchmarking

Data obtained in this study and from a meta-analysis (LOVATTO *et al.*, 2007) were collected to ascertain reference values for the main environmental sustainability indicators for Nile tilapia cage culture. These indicators' values generated the possibility of comparison from single treatment analysis. Without a reference, the indicator by itself doesn’t give relevant information concerning sustainability, once that it was developed as a comparison tool (VALENTI *et al*., 2018). These reference values were used to perform the benchmarking. This method of comparison, benchmarking, helps in improving processes and, consequently, the performance of the farms.

The benchmarking allows a continuous improvement process once that it is used to learn with other similar farms that have better performance. It allows to adapt the best practices from the other farms and achieve a more sustainable production (AGRINESS, 2014; BOYD *et al.*, 2007; CAMP, 1998). Also, environmental sustainability benchmarking reduced the possibility of wrong conclusions from the bad use of the ESI. For example, if compared two farms that didn't have proper management, generated a consider amount of pollutants, but one was slightly better than the other, when applying the environmental sustainability index, the conclusion is going to be that one farm had the best sustainable performance or it was more sustainable, even if both of them are not sustainable. These conclusions can lead a reader to understand that the observed numbers of the indicators showed a sustainable standard. The purpose of environmental sustainability benchmarking is not to create a "standard" value, but it is to show achievable improvement goals for each scenario.

As sort of an example, it will be shown an application of the benchmarking with some results from farm A. When comparing the indicators use of phosphorus, efficiency on the use of phosphorus and potential of phosphorus eutrophication, farm A had a performance of 21, 24 and 37% worse than the average, respectively. These comparisons point to the necessity of verifying feed balance and ingredients. The levels of phosphorus in the 6mm and 8mm feed are around 60% higher when compared to farm C, which had one of the best performance on these indicators.

There is a certain institutional incapacity of Brazil and other countries in fostering aquaculture on adequate lines (BUENO *et al.*, 2015). Although CONAMA regulates parameters to implement aquaculture systems in reservoirs and dams, monitoring, following up the development of the sector and its technologies are inefficiency without the assistance of modern decision-taking technologies. Since many environmental aspects need to be considered and interpreted, a high level of theoretical and technical knowledge is required to work with this information. Indicators allow an easier interpretation of the environmental scenario. However, training is required to learn how to realize and interpret them. In this example, benchmarking allowed, in a simple way, the identification of the main limitation that was affecting the environmental sustainability of farm A and the principal corrections necessary to cause a real positive impact.

5. CONCLUSIONS

Through the environmental sustainability index was possible to conclude that the farms B (medium-scale) and C (small-scale) were the most environmentally sustainable. The use of indicators and index are adequate and effective to evaluate the environmental sustainability benchmarking in aquaculture. The main aspects of the system were detected, identified and quantified. It was possible to achieve a reference value for the main environmental sustainability indicators of cultures of Nile tilapia in reservoirs and dams. With the demand for methods to monitor and measure the sustainability of aquaculture in reservoirs, mainly related to environmental impacts, this tool shows great potential to meet this demand. Environmental benchmarking is a way to develop a process of constant improvement. In this way, the farms can learn with what has been done and reduce the impacts on the environment.

The environmental sustainability index and benchmarking have proven to be the way to use ESI to achieve more sustainable aquaculture. It can be an important management tool for aquaculture certification programs due to the development of reference values for the indicators. The application of this tool can improve the safety of the growth of aquaculture, once that it establishes a continuous improvement of the production with the decrease of the environmental impact. This decrease creates the prosperity of the enterprise, once that the use of the main limiting factor (natural resource) becomes increasingly efficient.

However, reliable and systematic reference indicators are required for the application of benchmarking tools. It is necessary to increase the number of enterprises that were used to achieve these averages for each indicator. In this way, the numbers obtained are going to become more reliable to the reality of production in Brazil or worldwide. Nevertheless, the methods to collect this data need to be enhanced so that they can be more accessible, and also more efficient and able to apply more constantly. The use of monitoring sensors can be an alternative to improve the use of this tool by creating big data to improve the accuracy of the indicator reference values. But the cost of sensors may be a limiting factor for their use. Studies to develop more effective techniques of data collection and processing of this data need to be developed, to make benchmarking more accurate and achieve the best performance of this tool.

6.REFERENCES

ADGER, W. N. (2000). Social and ecological resilience: are they related? Progress in Human Geography, Londres, v.24, n.3, p.347-364.

AGRINESS (2014). Suino.Cultura: como o Pensamento+1 pode transformar o seu negócio. Florianópolis. 220p.

ALMEIDA, R. (2013). Indicadores de sustentabilidade do cultivo de tilápia do Nilo (*Oreochromis niloticus*) em tanques-rede em um reservatório tropical. Dissertação (mestrado) - Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 48p.

ALMEIDA, T. F. (2017). Lambaricultura como forma de desenvolvimento sustentável de comunidades rurais remanscentes de áreas protegidas no Brasil. Dissertação (mestrado) – Instituto de Biociências, Universidade Estadual Paulista (UNESP), São Vicente, São Paulo – Brasil. 49p.

AOAC. (1995). Official Methods of Analysis, 16th ed. AOAC International, Washington, DC.

AOAC. (2000). ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS. *Official Methods of Analysis of the Association of Official Analytical Chemists*, 16th ed., v. 1, Arlington: A.O.A.C., 2000, chapter 3. p 4. (method 985.01).

APHA. (2005). Standard methods for the examination of water and wastewater. American Public Health Association, Washington, DC.

BALLESTER-MOLTÓ, M.; SANCHEZ-JEREZ, P.; CEREZO-VALVERDE, J.; AGUADO-GIMÉNEZ, F. (2017). Particulate waste outflow from fish-farming cages. How much is uneaten feed? *Mar. Pollut. Bull.,* v.119, p.23-30.

BOYD, C. E.; TUCKER, C. S. (1998). Pond Aquaculture Water Quality Management. Boston: Kluwer Academic Publishers. 700p.

BOYD, C. E. *et al*. (2003). Best management practices for channel catfish farming in Alabama. Alabama: Alabama Catfish Producers, 2003. (Special report, n. 1).

BOYD, C. E., TUCKER, C.; MCNEVIN, A.; BOSTICK, K.; CLAY, J. (2007). Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Reviews in Fisheries Science*. v.15, p.327-360.

BRASIL. (2009). Conselho Nacional do Meio Ambiente. Resolução CONAMA nº 413, de 26 de Julho de 2009. Dispõe sobre o licenciamento ambiental da aquicultura, e dá outras providências. Diário Oficial da União, Brasília, n. 122, 30 de junho de 2009, p.126-129.

BUENO, G. W. (2015). Modelo bioenergético nutricional e balanço de massas para o monitoramento e estimativa de efluentes da produção comercial de tilápia do Nilo (*Oreochromis niloticus*) em reservatório tropical. Brasília: Faculdade de Agronomia e Medicina Veterinária, Universidade de Brasília, 2015, 118p. *Tese (Tese em Ciências Animais)* - Faculdade de Agronomia e Medicina Veterinária da Universidade de Brasília.

BUENO, G. W.; BUREAU, D.; SKIPPER-HORTON, J.; ROUBACH, R.; MATTOS, F. T.; BERNAL, F. E. M. (2017). Mathematical modeling for the management of the carrying capacity of aquaculture enterprises in lakes and reservoirs. *Pesq. Agropec. Bras.* v.52, n.9, p.695-706.

BUENO, G. W.; MARENGONI, N. G.; GONÇALVES JÚNIOR, A. C.; BOSCOLO, W. R.; TEIXEIRA, R. A. (2008). Estado trófico e bioacumulação do fósforo total no cultivo de peixes em tanques-rede na área aquícola do reservatório de Itaipu. *Acta Scientiarum Biological Sciences*, v.30, n.3, p.237-243.

BUENO, G. W.; OSTRENSKY, A.; CANZI, C.; MATOS, F.T.; ROUBACH, R. (2015). Implementation of aquaculture parks in Federal Government waters in Brazil. Rev. Aquac., v.7, n.1, p.1-12.

CAMP, R. C. (1998). *Benchmarking*: o caminho da qualidade total. 3.ed. São Paulo: Pioneira. 250p.

CETESB. (2009). Qualidade das águas interiores no estado de São Paulo. São Paulo: SMA.

CONAMA- Brasil (2005). Resolução nº 357 de 17 de março de 2005. Dispõe sobre a classificação dos corpos de água e diretrizes ambientais para o seu enquadramento, bem como estabelece as condições e padrões de lançamento de efluentes, e dá outras providências. Diário Oficial [da] União: seção 1, Brasília, DF, n. 053, p.58-63, 18 mar. 2005.

COSTA, C. M. (2019). Sustainability of Pacific Whiteleg shrimp farming according to levels of intensification. Tese (Doutorado) – Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 101p.

COSTA, M.L.S.; MELO, F.P.; CORREIA, E.S. (2009). Efeitos de diferentes níveis protéicos da ração no crescimento na tilápia do Nilo (*Oreochromis niloticus* Linnaeus, 1757), variedade chitralada, criadas em tanques-rede. *Boletim do Instituto de Pesca*, v.35, n.2, p.285-294.

DAVID, F. S.; PROENÇA, D. C.; VALENTI, W. C. (2017a). Nitrogen budget in integrated aquaculture systems with Nile tilapia and Amazon River prawn. *Aquaculture International*, v.25, n.5, p.1733-1746.

DAVID, F. S.; PROENÇA, D. C.; VALENTI, W. C. (2017b). Phosphorus Budget in integrated multitrophic aquaculture systems with nile Tilapia, *Oreochromis niloticus*, and Amazon River Prawn, *Macrobrachium amazonicum*. *Journal of the World Aquaculture Society*, v.48, n.3, p.402–414.

DUMAS, A.; FRANCE, J.; BUREAU, D. P. (2010). Modelling growth and body composition in fish nutrition: where have we been and where are we going? *Aquaculture Research*, v.41, p.161-181.

ENGLE, C. R. (2019). Bringing aquaculture sustainability down to earth. *Journal of the World Aquaculture Society*, v.50, p.246-248. DOI: 10.1111/jwas.12609

FAST A. W.; LESTER L. J. (1992). Marine shrimp culture: principles and practices. *Developments in Aquaculture and Fisheries Science*, v.23, 862p.

FIGUEIREDO, B. R.; BORBA, R. P.; ANGÉLICA, R. S. (2007). Arsenic occurrence in Brazil and human exposure. *Environ Geochem Health*, v.29, p.109–118. https://doi.org/10.1007/s10653-006-9074-9

FOOD AND AGRICULTURAL ORGANIZATION - FAO (2016). *The State of World Fisheries and Aquaculture. Contributing to food security and nutrition for all.* Rome, 200p.

FURUYA, W. M.; BOTARO, D.; MACEDO, R. M. G.; SANTOS, V. G.; SILVA, L. C. R.; SILVA, T. C.; FURUYA, V. R. B.; SALES, P. J. P. (2005). Aplicação do conceito de proteína ideal para redução dos níveis de proteína em dietas para tilápia-do-nilo (*Oreochromis niloticus*). *Revista Brasileira de Zootecnia*, v.34, p.1433-1441.

GIACOMINI, P. (2008). Use of the dairy records database to establish benchmarks and estimates for potential economic improvements of individual herds. Proceedings of the 36th ICAR Biennial Session, ICAR Technical Series No. 13, Niagara Falls, USA, p.221-225.

GODOY, E. M. (2019). Indicadores de sustentabilidade ambiental aplicados em pisciculturas familiares produtoras de tilápia do Nilo (*Oreochromis niloticus*) em sistema semi-intensivo. Trabalho de Graduação (Bacharel) – Universidade Estadual Paulista, Câmpus Experimental de Registro. Registro, 46p.

GONÇALVES, F. H. A. S. B. (2017). Sustentabilidade dos sistemas de produção do lambari-do-rabo-amarelo. Tese (doutorado) - Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 149p.

GILSON, F. D. A. (2019). Farm size influence on sustainability by tambatinga production in the Northeast region of Brazil. Tese (doutorado) – Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 134p.

HARDY, R. W.; GATLIN, D. (2002). Nutritional strategies to reduce nutrient losses in intensive aquaculture. In: Cruz-Suárez, L. E., Ricque-Marie, D., TapiaSalazar, M., Gaxiola-Cortés, M. G., Simoes, N. (Eds.). Avances en Nutrición Acuícola VI. Memorias del VI Simposium Internacional de NutriciónAcuícola. 3 al 6 de Septiembre del 2002. Cancún, Quintana Roo, México.

HOULIHAN, D.; BOUJARD, T.; JOBLING, M. (2001). Food Intake in Fish. Blackwell Science, Oxford, 440p.

IPCC. (2008). 2006 IPCC Guidelines for National Greenhouse Gas Inventories – A primer, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Miwa K., Srivastava N. and Tanabe K. (eds). Published: IGES, Japan.

ISLAM, M. S. (2002). Evaluation of supplementary feeds for semi-intensive pond culture of mahseer, *Tor putitora* (Hamilton). *Aquaculture*. v.212, p.263-276.

IWAMA, G. K.; TAUTZ, A. F. (1981). A simple growth model for salmonids in hatcheries. Can. J. Fish. Aquat. Sci., v.38, p.649-656.

JENSEN, T.; DEMPSTER, E.B.; THORSTAD, I.; UGLEM, A. F. (2010). Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. Aquac. Environ Interact v.1, p.71–83.

KIMPARA, J. M.; ZAJDBAND, A. D.; VALENTI, W. C. (2012). Métodos para medir a sustentabilidade da aquicultura. *EMBRAPA Meio Norte*. Teresina. 72p.

LOVATTO, P. A.; LEHNEN, C. R.; ANDRETTA, I.; CARVALHO, A. D; HAUSCHILD, L. (2007). Meta-analysis in scientific research: A methodological approach. *Brazilian Journal of Animal Science,* v.36, p.285-294.

MATVIENKO, B.; SIKAR, E.; ROSA, L. P.; SANTOS, M. A.; FILIPPO, R.; CIMBLERIS, A. C. P. (2001). Gas release from a reservoir in the filling stage. *International association of theoretical and applied limnology - Proceedings*, v.27, n.3, p.1415–1419.

MCDOUGALL, R. (2012). Why benchmarking is important. Proceedings of the 2012 London Swine Conference, London, Canada, p.59-60.

MECHI, A.; SANCHES, D. L. (2010). The Environmental Impact of Mining in the State of São Paulo. *Estudos Avançados*, v.24, n.68, p.209-220. https://dx.doi.org/10.1590/S0103-40142010000100016

MICHELSEN, O. B. (1957). Photometric determination of phosphorus as molybdovanadophosphoric acid. *Analytical Chemistry*, v.29, p.60–62.

MOTTA, R. S. (1997). Manual para valoração econômica de recursos ambientais. *IPEA/MMA.* Rio de Janeiro. 242p.

MOURA, R. S. T.; VALENTI, W. C.; HENRY-SILVA, G. G. (2016). Sustainability of Nile tilapia netcage culture in a reservoir in a semi-arid region. *Ecol. Ind.*, v.66, p.574–582.

NAKAMURA, M. (1957). The series of chemical experiments. *B. Chem. Soe. Jap*., v.23, p.528-532.

NESS, B.; URBEL-PIIRSALU, E.; ANDERBERG, S.; OLSSON, L. (2007). Categorising tools for sustainability assessment. *Ecol. Econ.*, v.60, p.498–508.

ODUM, H. T. (1986). Emergy in ecosystems. In: POLUNIN, N. (Ed.). Environmental Monographs and Symposia. New York: John Wiley. p.337-369.

ODUM, H. T. (1988). Self-Organization, Transformity, and Information. Science, Washington, v.242, p.1132-1139.

PAPATRYPHON, E., PETIT, J., KAUSHIK, S., VAN DER WERF, H., (2004). Environmental impactassessment salmonid feeds using life cycle assessment (LCA). Ambio, v.33, n.6, p.316–323.

PEIXE BR. (2019). Anuário Peixe BR da Piscicultura 2019. Available at: https://www.peixebr.com.br/Anuario2019/AnuarioPeixeBR2019.pdf. Acessed in: June, 18th, 2019.

PEREIRA, S. A. (2019). Viabilidade econômica e sustentabilidade do cultivo da macroalga *Hypnea pseudomusciformis*. Dissertação (mestrado) - Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 69p.

PROENÇA, D. C. (2013). Aplicação de indicadores e índices para avaliar a sustentabilidade ambiental em um sistema de aquicultura integrado e multitrófico com diferentes substratos. Dissertação (mestrado) - Universidade Estadual Paulista, Centro de Aquicultura. Jaboticabal, 33p.

REES, M.; WACKERNAGEL, W. (1996). Urban ecological footprints: Why cities cannot be sustainable - And why they are a key to sustainability. Environmental Impact Assessment Review, Amsterdam, v.16, n.4-6, p.223-248.

ROLIM, G. S.; CAMARGO, M. B. P.; LANIA, D. G.; MORAES, J. F. L. (2007). Classificação climática de Köppen e de Thornthwaite e sua aplicabilidade na determinação de zonas agroclimáticas para o estado de são Paulo. *Bragantia*, v.66, n.4, p.711-720. https://dx.doi.org/10.1590/S0006-87052007000400022

SCIENCEMAN, D. M. (1987) Energy and emergy. In: PILLET, G., MUROTA, T. (Ed.). Environmental economics: the analysis of a major interface. Geneva: Leimgruber, 1987. p. 257-276.

VALENTI, W. C. (2008). A aqüicultura brasileira é sustentável?. *Aqüic. Pesca,* p.36-44.

VALENTI, W.C.; KIMPARA, J.M.; PRETO, B.L.; MORAES-VALENTI, P. (2018). Indicators of sustainability to assess aquaculture systems. *Ecological Indicators*. v.88, p.402-413.

WARHURST, A., (2002). Sustainability Indicators and Sustainability Performance Management. Report to the Project: Mining, Minerals and Sustainable Development (MMSD). International Institute for Environment and Development (IIED). Warwick, England.

WATANABE, W.O.; OLLA, L.B.; WICKLUND, R.I.; HEAD, W.D. (1997). Saltwater culture of the Florida Red Tilápia and other saline tolerant Tilápias: Review. In: COSTA-PIERCE, B.A.; RAKOCY, J.E. (Eds.) Tilapia Aquaculture in the Americas, 1st ed., Baton Rouge: *World Aquaculture Society*. p.54-141.

CONSIDERAÇÕES FINAIS

Utilizando o índice de sustentabilidade ambiental foi possível concluir que as fazendas B (larga-escala) e C (pequena-escala) foram as mais sustentáveis ambientalmente. O uso de indicadores e índices é adequado e eficaz para avaliar o *benchmarking* da sustentabilidade ambiental na aquicultura. Os principais aspectos do sistema foram detectados, identificados e quantificados. Foi possível atingir um valor de referência para os principais indicadores de sustentabilidade ambiental em criação de tilápia do Nilo em represas e reservatórios. Com a demanda por métodos para monitorar e medir a sustentabilidade da aquicultura em reservatórios, principalmente relacionados aos impactos ambientais, esta ferramenta mostra um grande potencial para suprir esta demanda. O *benchmarking* ambiental é uma maneira para desenvolver um processo de melhoria constante. Dessa forma, as fazendas podem aprender com o que foi feito e reduzir os impactos no meio ambiente.

O índice de sustentabilidade ambiental e o *benchmarking* mostraram ser a maneira de usar os indicadores de sustentabilidade ambiental para alcançar uma aquicultura mais sustentável. Essa pode ser uma ferramenta importante para programas de certificação de aquicultura devido ao desenvolvimento de valores de referência para os indicadores. A aplicação desta ferramenta pode melhorar a segurança do crescimento da aquicultura, uma vez que estabelece uma melhoria contínua da produção com a diminuição do impacto ambiental. Essa diminuição cria a prosperidade da empresa, uma vez que o uso do principal fator limitante (recurso natural) se torna cada vez mais eficiente.

No entanto, indicadores de referência confiáveis e sistemáticos são necessários para a aplicação do *benchmarking*. É necessário aumentar o número de empreendimentos que foram usadas para atingir essas médias para cada indicador. Dessa forma, os números obtidos se tornarão mais fidedignos à realidade da produção no Brasil ou no mundo. Contudo, se faz necessário a otimização das metodologias de análise, para que as mesmas possam ser feitas de maneira mais acessível, com maior repetibilidade e eficiência. O uso de sensores de monitoramento pode ser uma alternativa para melhorar o uso dessa ferramenta, criando um “big data” para melhorar a precisão dos valores padrão dos indicadores. O custo dos sensores pode ser um fator limitante para seu uso. Estudos para desenvolver técnicas mais eficazes de coleta de dados e de processamento dos mesmos precisam ser desenvolvidos, para tornar o *benchmarking* mais preciso e obter o melhor desempenho dessa ferramenta.