ASSESSING THE SUSTAINABILITY OF MARINE SHRIMP (GROW-OUT IN PONDS IN A SEMI-ARID REGION)

ABSTRACT: The objective of this study was to evaluate the sustainability of *Litopenaeus vannamei* production in pond systems subjected to different management strategies, with consideration given to economic, environmental and social aspects. The experimental design was completely randomized and consisted of three treatments and four replications with a duration of approximately 79 days. The treatments differed according to the stocking density of the shrimps: M1: 92 shrimps.m^{-2}; M2: 14 shrimps.m^{-2} and M3: 8 shrimps. m^{-2}. For the evaluation of the social dimension, a negative income distribution was shown for the M1 treatment due to the high costs of production and the accumulation losses for this management strategy. The M2 and M3 treatments showed reduced income distributions, with labor remunerations of US$ 0.21 and US$ 0.32 and representing 48 and 32% of total operating costs (TOC). The ratio of direct and indirect income and generation of jobs was considered low for all of the treatments. In the economic evaluation, the M2 and M3 treatments showed greater feasibility probably due to the reduced operational costs and investments to obtain post larvae, feed, fertilizers and labor. The greater distance from the economic dimension for the M1 treatment may be associated with the high gross revenue (GR) and total operating costs (TOC). The M2 and M3 treatments showed positive internal rates of return (IRR) due to the high selling prices per kilogram of shrimp during the experimental period (2016). The positive IRR indicated economic feasibility for the M2 and M3 treatments while the M1 treatment showed a negative IRR due to showing no profits and therefore, being unsustainable economically. The payback period (PP) in the M1 was negative as well. The PPs in M3 and M2 were positive, with the M3 having a reduced PP as a function of the shorter cultivation period. In the environmental dimension, the cultures presented moderate sustainability for all treatments with the M1 treatment being the most viable. Environmental sustainability was influenced most by the generation of solid. It is worth noting that the white spot syndrome virus weakened the economic and social sustainability for all of the treatments. For the sustainability modeling, the M2 and M3 treatments were the most balanced and thus received the highest overall sustainability index. The same treatments were the most economically sustainable perhaps due to lower operating costs and adequate selling prices of the shrimp. The M1 treatment was the most environmentally favorable treatment and had a social tendency. It can be concluded that the shrimp monoculture carried out with high initial stocking densities is unable to guarantee the return of invested capital. The M2 and M3 treatments were only economically feasible due to the high prices paid per kilogram of shrimp. However, economic feasibility of these two treatments coincided with low creation of employment opportunities and income, a decrease in social sustainability, and an increased impact on the environment.

Keywords: Shrimp aquaculture, indicators of sustainability, modeling, ponds.

1. INTRODUCTION

Aquaculture is one of the fastest growing agriculture industries around the world. Over the past decades, aquaculture has led to a robust and diversified human food supply comprised of products with high quality and added value. The expansion of aquaculture should employ strategies to increase production while minimizing water exchange, greenhouse gas emissions, and recycling the effluents (Pereira and Rocha, 2015; Moura, et al., 2016; Araújo and Valenti, 2017; König, et al., 2018).

Marine shrimps are important aquaculture commodities. In 2018, global shrimp mariculture was responsible for nearly 4 million tonnes of traded product, which was an increase of approximately 4% when compared to global production in 2017 (FAO, 2020). The white shrimp, *Litopenaeus vannamei*, is the most farmed marine shrimp around the world. This species tolerates high stocking densities and shows high productivity. Nevertheless, white shrimp culture has suffered economic losses due to disease outbreaks, most notably the white spot syndrome virus (WSSV). Outbreaks of WSSV have led to mass mortalities of entire shrimp stocks around the world and have been recorded in Brazil during the present decade (Tran et al., 2013 and Nunan et al., 2014; Maia, et al., 2016). Various management practices have been applied to mitigate the impacts of WSSV while maintaining adequate productivity. These practices focus on improving environmental conditions by reducing stocking density and water exchange, using highly digestible feeds with low levels of protein, performing early harvests, among other strategies. Other management practices aim to reduce pollution of the surrounding aquatic environment and atmosphere and improve the quality of life of people involved in the activity, can increase environmental and social sustainability and may have added value to the production (Castillo-Soriano et al., 2013; Brito et al., 2014; Brito et al., 2016).

Nevertheless, the efficacy of each management strategy to improve sustainability should be assessed.

A holistic approach to evaluate the overall sustainability of aquaculture should include the three dimensions of sustainability, i.e., economic, environmental and social. The use of a set of quantitative indicators that reflect the key features of the dimensions of sustainability has facilitated the identification of strengths and weaknesses for sustainable development (Valenti et al., 2011; Moura et al, 2016; IISD, 2017; Valenti et al, 2018). The determination of the indicators may be complemented by the application of the DPSIR (*Drivers-Pressure-State-Impact-Response*) model, which combines information from several indicators with management information. This model carries out a systemic evaluation of data on economic, environmental and social interactions in a single system to reveal the most sustainable management strategy of a resource and suggest the most important indicators (Nobre et al, 2010; Moura et al., 2016). This approach has been applied to the management of natural resources in Europe using computer models such as the MULINO *mDSS* (Giupponi, 2007), which provides an interface between managers to assist in decision-making. The objective of this study was to evaluate the economic, environmental and social sustainability of white shrimp (*L. vannamei*) aquaculture through the application of a set of indicators and the DPSIR modeling concept, comparing production systems that used different management strategies.

2. MATERIALS AND METHODS

2.1. AREA OF STUDY

The present study was carried out at a commercial marine shrimp farm in the municipality of Mossoró, Rio Grande do Norte - Brazil. The farm is located near a hypersaline estuary of the Apodi river, with the geographic coordinates of Long – 690985,31E in Lat – 9435502,43 N (UTM), in a region with many salt flats. The farm has an area of 800 ha distributed among 80 ponds of 0.26 to 2.6 ha, which are used for the grow-out of *L. vannamei* (8 to 100 shrimps.m^{-2}). The water was sourced from both the Apodi river and from underground artisan wells. The region has a tropical and semi-arid climate of BSwh' according to the Köppen classification system with an average temperature of 27.4ºC, an annual rainfall average of 685.3 mm and an average relative humidity of 68.9%.

2.2. EXPERIMENTAL DESIGN

The experimental design was completely randomized with three treatments and four replicates. The 12 experimental units were earthen ponds with areas ranging from 2600 to 26000 m² (ha). The ponds were drained, sterilized and maintained sanitary and empty for thirty days before being stocked with the *L. vannamei* post-larvae. The shrimp were stocked with a mean individual mass of 4 mg. Three treatments were defined based on different initial stocking densities and management strategies: Management strategy 1 (M1): four grow-out ponds were initially stocked with ~239 million post larvae (92 shrimps.m^{-2}). The production system was managed as a single grow-out phase in which the post-larvae were stocked directly in ponds immediately after the larviculture. The ponds were initially fertilized with a mixture of 100 kg.ha^{-1} of wheat bran, 30 kg.ha^{-1} of calcium nitrate, 20 kg.ha^{-1} of silicate and 20 kg.ha^{-1} of molasses, and were maintained with biweekly fertilizations of 30 kg.ha^{-1} calcium nitrate and weekly of 10 kg.ha^{-1} of molasses. Management strategy 2 (M2): four grow-out ponds were initially stocked with 364 million post-larvae (14 shrimps.m^{-2}). The production system was managed as a single-phase grow-out with an initial fertilization similar to the M1 treatment, but with no maintenance fertilizations. Management strategy 3 (M3): this treatment consisted of two distinct growth phases. The first phase was an intermediate nursery phase carried out in raceways stocked with 1,000 shrimps.m^{-2} and lasted for 30 days. Each raceway was covered with a canvas of 20x100 m. The raceways were initially fertilized using a mixture of 250 kg.ha^{-1} of wheat bran, 45 kg.ha^{-1} of calcium nitrate and 40 kg.ha^{-1} of molasses. A probiotic mixture comprised of *Bacillus* spp. and *Lactobacillus* sp. were added at 0.2 kg.ha^{-1} to the production system as well. The probiotic mix was previously activated in tanks of 1000 liters for 24 hours with molasses and water from the raceway system used in the experiment. Probiotics were inoculated weekly at 0.1 kg.ha^{-1} and molasses at 20 kg.ha^{-1} to maintain a C/N ratio above 10 as suggested by Avnimelech (2009). In the second phase, juveniles of *L. vannamei* were harvested from the raceways with a mean individual biomass of 0.98 ± 0.05 g and stocked in four grow-out ponds with an initial population of 208 million post-larvae (8 shrimps.m^{-2}). Each of the grow-out ponds was initially fertilized with 30 kg.ha^{-1} of calcium nitrate and 100 kg.ha^{-1} of dolomitic limestone. The ponds were fertilized weekly using 10 kg.ha^{-1} of calcium nitrate until the harvest.

Feed in all treatments was distributed by hand. The shrimps were initially fed four times daily at 10% of the total biomass until attaining a mean individual mass of approximately 1 g. The feeding rate was then gradually reduced to 2% of the biomass until the end of the experiment and divided into two daily feedings. The mean individual mass of the shrimps was estimated weekly by weighing a sample of the population. The cultures lasted ~79 days. After the harvest, survival was estimated by dividing the total biomass by the mean individual shrimp mass. The apparent feed conversion ratio (AFC) was estimated by dividing the total mass of feed input by the total shrimp biomass harvested (Table 1). The economic, environmental and social sustainability was evaluated based on production per year.

Table 1. Mean values and standard deviations of the productive performance characteristics for the different treatments of the grow-out phase of *L. vannamei*. Different letters indicate significant differences according to the Tukey test ($p<0.05$).

Parameters	Treatments		
	M1	M2	M3
Survival (%)	42.9±5.5a	12.2±3.5b	39.3±0.09a
Initial individual mass (g)	0.004a	0.004a	0.98b
Final individual mass (g)	6.3±0.4b	9.4±1.8a	6.9±0.5b
Apparent feed conversion ratio (AFCR)	2.95±0.47a	1.44±0.41b	0.22±0.08c
Cycles per year (number)	4.6	4.3	7.3
Yield (kg.ha^{-1})	652±99a	332±149b	219±57b

The three dimensions of sustainability (economic, environmental and social) were assessed using 42 indicators (Table 2) proposed by Valenti et al. (2018). The data used to calculate the indicators were described by O'Ryan and Pereira, 2015; Chowdhury et al., 2015; Ting et al. 2015 and Moura et al., 2016. Specific methodologies were applied during each sampling period (described below) to calculate the indicators using the collected data. The equations used to calculate the indicators are shown in Annexes I, II and III.

Table 2. Indicators of economic, environmental and social sustainability (Valenti et al., 2018).

Economic Dimension	Environmental Dimension	Social Dimension
Gross revenue	Use of space	Salary equaliy
Total operating cost	Water dependence	Proportional cost of work
Investment income ratio	Proportion of renewable energy	Income distribution
Internal rate of return	Eutrophication potential	Remuneration per production

Payback period	General pollution	Race inclusion
Cost-benefit ratio	Hormone pollution	Gender inclusion
Net present value	Accumulation of phosphorus	Age inclusion
Profit	Accumulation of organic material	Work per area
Returnability index	Use of space	Work per production
Profitability index	Risk with cultivated species	Creation of direct occupation
Product diversity		Creation of work positions
Market diversity		Portion of self-employed
		Use of local laborers
		Fixation of income
		Local consumption
		Health benefits
		Education
		Permanence in the activity
		Participation in community activities
		Work safety

2.3. ECONOMIC DIMENSION

Economic sustainability consisted of 12 indicators divided among four main categories: a) efficient use of financial resources; b) resilience capacity; c) capacity to absorb costs of negative externalities; and d) the capacity to generate capital for reinvestment. All of the economic data were collected together from Company, provided by the owners and those associated with the financial transactions researched for the shrimp market in the state of Rio Grande do Norte for the year 2016.

All equipment, utensils, supplies and management used in the production were recorded. The cost-return and cash flow analyses were carried out with an initial investment that included the construction of ponds, sheds, water supply, drainage system, kayaks, pumps, aerators and other items of lower cost. The gross revenue (GR) was calculated based on the production, average selling price of shrimp in the year 2016 and the mean final individual biomass of the shrimps (Table 3). Profit was calculated by the difference between gross revenue and production costs, including taxes.

Table 3. Average selling prices of the shrimps practiced in the markets of Rio Grande do Norte and Ceará during the year 2016.

Classifications (g)	6.5-8.5	8.6-10.5	10.6-12.5	12.6-14.5	14.6-16.5
Price (US$)	6.46 to 7.69	7.84 to 9.23	9.38 to 10.46	10.61 to 11.07	11.23 to11.69

Source:Survey carried out with local producers.

2.4. ENVIRONMENTAL DIMENSION

Environmental sustainability was evaluated using a set of 10 indicators. The sediment generated in the production systems was quantified biweekly using sedimentation chambers placed in the grow-out ponds. The sedimentation chambers were placed directly in the grow-out ponds in duplicate for the three treatments and remained submerged for 24 hours. Each sediment sample was weighed and the particulate matter and organic material contents were calculated according to Buffon et al. (2009). Water samples were taken biweekly from the sedimentation chambers to determine particulate matter, total nitrogen (Koroleff, 1976), total phosphorus and orthophosphate (Golterman et al., 1978). Ammonia, nitrite and nitrate were determined according to Mackereth et al. (1978), and organic and inorganic carbon were determined using a VARIO-TOC carbon analyzer.

Emissions from diffusion and bubbles of CH_4, CO_2, N_2O, O_2 and N_2 gases were measured at the beginning, middle and end of the culture in each experimental unit. The gas emission through surface diffusion ($mg.m^{-2}.d^{-1}$) was estimated using a gas chamber

(Santos et al, 2005). The gases were sampled by positioning the diffusion chamber facing downwards on the surface of the water. The gases emanating from the ponds tend to gradually accumulate in the air trapped inside the chamber. Gas samples were then taken from the diffusion chamber in a time series (0, 1, 2, and 4 minutes) using 30 ml syringes. Samples were subsequently stored in gasometric vials. The emission of gases through diffusion was measured for both the day and night periods.

The gases emitted through bubbles were estimated using inverted funnels with a diameter of 0.0707 m^2, and submerged just below the pond water surface as described in Santos et al., (2005). A graduated recipient filled with water was attached at the top of each funnel. The funnels remained in the ponds for 24 hours. The accumulated gas at the end of this period was withdrawn to record its volume and was stored in gasometric vials. The vials were then transported to the laboratory to determine the compositions of methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), oxygen (O_2) and nitrogen (N_2) using gas chromatography. The gas compositions were given in % and then converted to ppm. The mean daily emissions of all gases through diffusion and bubbling in each treatment were combined to obtain the total flow of each gas ($mg.m^{-2}.d^{-1}$) over a 24-hour period and to observe if the shrimp production systems emit or absorb greenhouse gases.

2.5. SOCIAL DIMENSION

The social dimension consisted of 22 indicators divided among four main categories: a) social equity; b) the distribution of income; c) equal opportunities; and d) the generation of jobs and benefits for local communities. The data were acquired from the owners and employees of the company using semi-structured questionnaires, as well as a survey carried out with the public agencies of

Brazilian Institute of Geography and Statistics - IBGE and Ministry of Fisheries and Aquaculture - MPA for information about the municipality.

2.6. DPSIR/MULINO MODELING

The concept model of the production systems was implemented using the software *Multisectorial, Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale* (MULINO *mDSS*) v5.12 (Giupponi, 2007). A subset of the original set of indicators was used as input data in this model, totaling 24 indicators distributed among the three dimensions of sustainability (economic, environmental and social) and according to the DPSIR criteria (Table 4). This subset consisted of indicators that were perceived to best reflect the changes in the system according to the models of the three treatments.

The selected indicators served as inputs in the *software* MULINO *mDSS* and were grouped according to the DPSIR criteria: (i) indicators of motor forces, considering the activity of shrimp production in earthen ponds; (ii) indicators of pressure on the ecosystem; (iii) indicators of the state of current conditions of the studied system; (iv) indicators of impacts caused by the activity; and (v) responses in terms of management to mitigate the impacts generated. A sensitivity analysis was conducted using a sub-routine of the program. This analysis evaluates the behavior of the models (treatments) in response to changes of each of the indicators and suggests the indicators that are the most important for the system. The most important indicators were considered as those in which small changes in their values strongly influence the sustainability of the system. Thus, an inadequate value would receive a value of zero and an excellent and attainable value would receive a value of 100. Then the scale was divided in equal or different portions according to the nature of the indicator.

A performance worse than the lowest value at the beginning of the scale received a value of zero and a performance better than the highest value received a value of 100. These indicators received twice the weight attributed to the others in the conceptual model. The *software* MULINO was used to do a comparative analysis to calculate the performance of the indicators for each scenario. In this manner, the treatments were evaluated in the *software* MULINO to simulate how the shrimp production systems would behave with different management strategies and stocking densities and thus, evaluate which scenario presents greater sustainability. The decision algorithm used was SAW (Simple Additive Weighting).

Table 4. Indicators of sustainability used in the *software* MULINO *mDSS* according to the rules of the DPSIR conceptual model.

Indicator	Weight	Criteria	Dimension
Annual profit	Motor force	0.249	Economic
Investment income ratio	Motor force	0.056	Economic
Work per production	Motor force	0.286	Social
Work per area	Motor force	0.006	Social
Accumulation of organic material	Pressure	0.055	Environmental
Accumulation of particulate matter	Pressure	0.006	Environmental
Accumulation of nitrogen	Pressure	0.011	Environmental
Accumulation of phosphorus	Pressure	0.022	Environmental
Gender inclusion	State	0.011	Social
Age inclusion	State	0.011	Social
Proportional cost of work	State	0.008	Social
Payback period	State	0.006	Environmental
Cost-benefit ratio	State	0.006	Economic
Remuneration per production	State	0.015	Social
Internal rate of return	State	0.007	Economic
Income distribution	State	0.006	Social
Eutrophication potential	Impact	0.008	Environmental
Water dependence	Pressure	0.007	Environmental
Energy use	Pressure	0.076	Environmental
Absorption and emission of CH4	Pressure	0.051	Environmental
Absorption and emission of N20	Pressure	0.063	Environmental
Absorption and emission of CO2	Pressure	0.075	Environmental
Annual production	Pressure	0.007	All
Changes in indicators	Response		All

3. RESULTS

3.1. INDICATORS OF ECONOMIC SUSTAINABILITY

All of the investment to construct the facility was carried out by the owners of the company. Initial investments included the construction of the ponds, sheds, kayaks, pumps, aerators and other items of lower cost such as screens, cutting boards, office supplies, etc., totaling US$ 29,311.53 for M1 and US$ 10,055.34 for M2 and M3 in the year 2016. Investments were calculated based on one hectare of cultivated area for a period of one year. Shrimp productivity (Kg.ha^{-1}year^{-1}) was 3,507 for M1, 1,430 for M2 and 1,601 for M3, which generated gross revenues of US$ 22,861.38 (M1), US$ 13,197.69 (M2) and US$ 12,311.73 (M3), respectively. Due to the high total operating costs (TOC) (Table 6), the M1 treatment showed a negative profit of US$ 40,419.98 while treatments M2 and M3 showed positive profits of US$ 5,346.25 and US$ 2,884.37, respectively. The diversity of production was low since the activity was carried out as shrimp monoculture and commercialized for human consumption in major markets in the states of São Paulo, Distrito Federal, Santa Catarina, Pernambuco, Ceará and Rio Grande do Norte (Table 5). These indicators are an average estimate of the production and selling prices of the product per kilogram (US$ 8.27) based on transactions in the Rio Grande do Norte market for the year 2016, estimated individually for each treatment.

Table 5. Values obtained for the indicators of economic sustainability for the different treatments of the grow-out of *L.vannamei*.

Indicators	M1	M2	M3
Ratio between Net Income and Initial Investment	-3,386.09	254.68	153.91
Annual Production (kg)	3,507	1,430	1,601
Gross Revenue (US$)	22,861.38	13,197.69	12,311.73
Total Operating Cost - TOC (US$)	63,374.93	7,854.41	9,427.36
Investment Income Ratio (US$)	-0.42	0.16	0.13
Internal Rate of Return (%)	-	33.70	28.89
Payback Period (yr)	- 0.82	8.61	6.34
Benefit-Cost Ratio (US$)	-3.93	1.05	0.68

Net Present Value (US$)	-394,860.87	37,256.76	11,775.45
Profit (US$)	-40,419.98	5,346.25	2,884.36
Returnability Index (RI)	0.36	1.68	1.31
Profitability Index (PI)	-1.81	0.33	0.32
Diversity of Product	1.00	1.00	1.00
Diversity of Market	6.00	6.00	6.00

3.2. INDICATORS OF ENVIRONMENTAL SUSTAINABILITY

The rates of sedimentation of particulate matter, ammonia, nitrite and total phosphorus were significantly higher in the M3 treatment when compared to the M1 and M2 treatments at the beginning of the production (15 days). Significant differences were observed between treatments for some of the sedimentation rates of the nutrients, showing a trend of reduction towards the end of the culture for the generation of particulate material (M1 and M3), ammonia, nitrate and total nitrogen. Increases were observed throughout the cultivation for the total phosphorus, TIC and TOC, while nitrite became stabilized (Table 6).

Table 6. Means (± standard deviation) for the sedimentation of particulate material, ammonia, nitrite, nitrate, total phosphorus, total nitrogen, total organic carbon, and total inorganic carbon for the M1, M2 and M3 treatments.

Treatment	Particulate material (mg/cm^2/day	Ammonia (ug/cm^2/day)	Nitrite (ug/cm^2/day)	Nitrate (ug/cm^2/day)	TP (ug/cm^2/day)	TN (mg/cm^2/day)	TOC (mg/cm^2/day)	TIC (mg/cm^2/day)
M1	14.601(±1.52)	4.95(±1.86)	0.12(±0.07)	20.66(±1.45)	35.16(±10.35)	0.022(±0.001)	0.568(±0.10)	0.800(±0.12)
M2	6.172(±0.86)	5.27(±1.32)	0.07(±0.03)	20.02(±0.97)	14.64(±2.65)	0.021(±0.002)	0.595(±0.07)	0.706(±0.14)
M3	22.031(±3.79)	8.16(±3.77)	3.73(±1.00)	23.43(±9.95)	64.79(±6.37)	0.028(±0.002)	0.692(±0.02)	0.800(±0.05)

The indicators of environmental sustainability showed water dependencies of 39,554; 89,608 and 103,881 m^{-3} per tonne of shrimp and space requirements of 1,534, 3.10 and 4.56 ha per tonne of shrimp for the M1, M2 and M3 treatments, respectively

(Table 7). The nitrogen accumulation was 1.71, 3.94 and 11.70 and phosphorus was 0.5, 0.7 and 3.3 kg per tonne of harvested product for the M1, M2 and M3 treatments, respectively. Renewable energy, general pollution and hormone pollution received a value of zero since none of these were used in the production systems.

The production systems accumulated particulate matter at rates of 141,110, 146,770 and 513,100 kg per tonne of shrimp produced in treatments M1, M2 and M3, respectively. The particulate matter consisted of 0.24, 0.52 and 0.05% of organic matter, which generated a discharge of 0.34, 0.77 and 0.27 kg of organic matter per kilogram of shrimp produced for the M1, M2 and M3 treatments, respectively. The eutrophication potential showed that the systems released 43.62, 52.36 and 7.14 for nitrogen and 9.25, 11.07 and 1.51 kg of phosphorus per tonne per production cycle for the treatments M1, M2 and M3, respectively (Table 7).

For the gases, methane (CH_4) emission was 19.6829 kg per tonne of shrimp produced in the M2 treatment and absorption was 4.8298 and 3.9627 kg per tonne of shrimp produced in the M1 and M3 treatments, respectively. Carbon dioxide (CO_2) emissions were 14.9757 and 47.8338 kg per tonne of shrimp produced in the M2 and M3 treatments, respectively, and absorption of CO_2 was 57.8827 kg per tonne of shrimp produced in M1. Nitrous oxide (N_2O) emissions were 0.038 and 0.7703 kg per kilogram of shrimp produced for the treatments M1 and M2, respectively. N_2O was absorbed at a rate of 0.0218 kg per tonne of shrimp produced in M3 (Table 7).

Table 7. Values obtained for the indicators of environmental sustainability for the different treatments of the grow-out of *L. vannamei* in earthen ponds for the treatments M1, M2 and M3.

	Treatments		
Indicators	M1	M2	M3
Use of Space (m^2/kg)	15.34	30.10	45.66
Water Dependence (m^3/t)	39,554	89,608	103,881
Uso of Energy (MJ/kg)	22,400	43,900	66,500
Proportion of Renewable Energy (%)	0	0	0
Use of Nitrogen (kgN/t)	153	74.88	11.44
Use of Phosphorus (kgP/t)	32.45	15.84	2.42
Accumulated of Nitrogen ($kgN.t^{-1}$)	1.71	3.94	11.70
Accumulated of Phosphorus ($kgP.t^{-1}$)	0.5	0.7	3.3
Efficiency in the Use of Nitrogen (%)	34	34	34
Efficiency in the Use of Phosphorus (%)	10	10	10
Production Actually Used (%)	60	60	60
Potential of Eutrophication (kgN/t)	43.62	52.36	7.14
Potential of Eutrophication (kgP/t)	9.25	11.07	1.51
Pollution General (kg/kg)	0	0	0
Pollution by Hormones (kg/kg)	0	0	0
Accumulation of OM (kgOM/t)	340	770	270
Accumulation of PM ($kgPM/t^1$)	141,111	146,770	513,100
Risk of Farmed Species	4	4	4
Emission and Absorption of CH_4 ($kgCH_4/t$)	-4.8298	19.6829	-3.9627
Emission and Absorption of CO_2 ($kgCO_2/t$)	-57.8827	14.9757	47.8338
Emission and Absorption of N_2O (kg N_2O/t)	0.038	0.7703	-0.0218

3.3. INDICATORS OF SOCIAL SUSTAINABILITY

The labor required to carry out the cultivations was 1.17 (M1), 1.46 (M2) and 2.04 (M3) man-hour-year per square meter ($mhy.m^{-2}$). The work required per unit of production was 0.01 man hours per kg of shrimp produced ($mh.kg^{-1}$) for the M1 treatment and 0.03 for the M2 and M3 treatments. The wage equity was 73% for M1, 70% for M2, and 69% for M3. Values of racial inclusion (100%), inclusion of gender (61%) and age inclusion (50%) were the same for all three treatments since no changes in the workforce occurred between the treatments. The income generated by the activity of the three treatments showed that 100% of the employee salaries were used within the municipality. The local consumption of shrimp was 0% since the production was commercialized to sell only at the capitals of the Rio Grande do Norte and other Brazilian states (Table 8).

The company offered no health benefits to employees and the education levels of the employees indicated that only 15% were currently involved in scholarly activities (Table 8). The permanence of each employee in the company was three years. Regarding the participation of employees in external community activities, 50% of the employees had ties with the rural union or fishermen colony (agriculture workers unions). Among the work safety items, the company provided 67% of the equipment and actions necessary to carry out activities with relative safety. Among the 15 items verified for the work safety indicator, five were considered irrelevant since they were considered of little or no use in shrimp farms. These items were the use of life jackets, safety glasses, equipment that alleviates physical exertion, use of machines and equipment by a qualified professional, and posted signs to warn of possible danger areas.

Table 8. Mean values obtained for indicators of social sustainability for the different treatments of the *L. vannamei* grow-out production.

	Treatments		
Social Sustainability Indicators	M1	M2	M3
Salary Equality (%)	73	70	69
Proportional Cost of Labor (%)	50	47	56
Income Distribution (US$)	-0.24	0.21	0.32
Remuneration of Work per Unit of Production (US$/kg)	9.08	2.60	3.31
Racial Inclusion (%)	100	100	100
Gender Inclusion (%)	61	61	61
Age Inclusion (%)	50	50	50
Required Work Per Unit of Occupied Area (MHY/m^2)	1.17	1.46	2.04
Required Work Per Unit of Work Per Production (MH/kg)	0.01	0.03	0.03
Investment to Create Direct Employment (ICDE) (UU$/jobs)	1,846	1,318	1,318
Investment to Create Total Employment (ICDE) (UU$/jobs)	861	615	615
Proportion of Self-Employments (%)	25	20	14
Use of local Workers (%)	50	60	50
Fixation of income (%)	85	85	85
Local Consumption of Production (%)	0	0	0
Access to Health-Insurance Programs	0	0	0
Schooling (%)	15	15	15
Permanence in the Activity (yr)	3	3	3
Permanence Owner the Activity (yr)	20	20	20

Participation in Outside Community Activities	50	50	50
Work safety (%)	67	67	67

3.4. MODELING OF SUSTAINABILITY

The overall sustainability showed different behaviors between treatments in relation to the three dimensions of sustainability in the model DPSIR/MULINO. The systems were considered sustainable when the distribution of the indicator set is towards the center of the triangle, while a distribution towards the edge of the triangle indicates sustainability in one or two of the dimensions (Figure 2). The M1 treatment showed a sustainability distributed toward the environmental dimension with a tendency towards the social dimension and was considered economically unviable. The M2 and M3 treatments showed distributions towards the economic dimension and were less distributed towards the environmental and social dimensions, indicating that these treatments are more economically sustainable. The M3 scenario had the highest overall sustainability index with a value of 62, followed by the M2 (60) and M1 (45) treatments (Table 9).

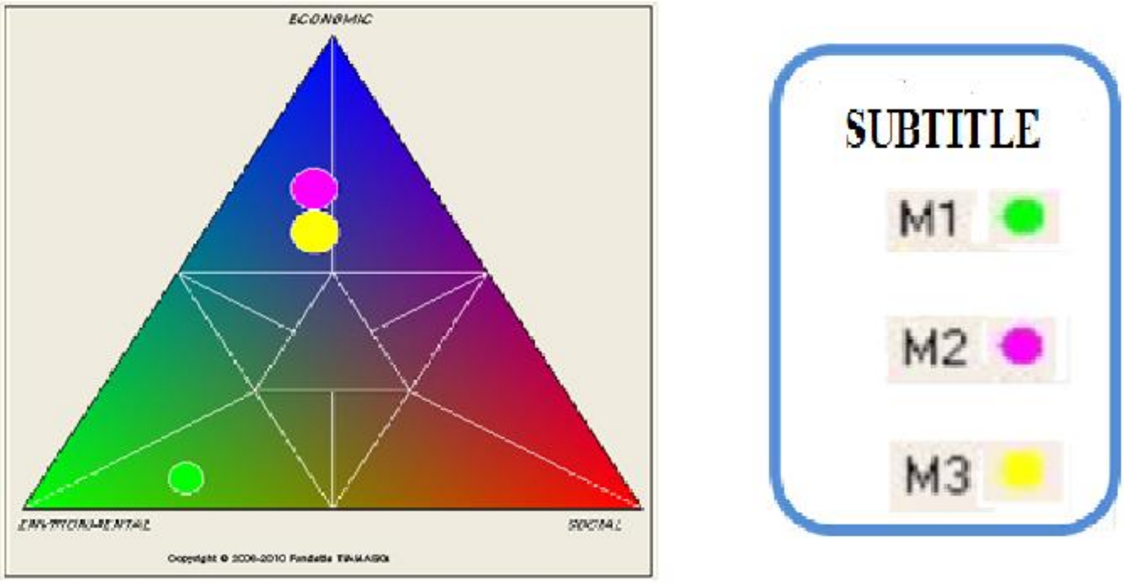

Figure 2. Triangle of sustainability for the different treatments of *L. vannamei* grow-out. The center of the triangle is considered the best overall sustainable scenario of the production system.

Table 9. Scores of sustainability generated by the software MULINO mDSS in the environmental, social, and economic dimensions for each treatments and general index of sustainability.

Scenario	Scores			Indices
	Environmental	Social	Economic	
M1	70	23	7	45
M2	19	13	68	60
M3	24	18	58	62

4. DISCUSSION

The shrimp productions showed little social sustainability for most of the indicators, employing 50% of the labor with little work per unit of area and per production. The reduced social sustainability may be related to a feed management that uses automation rather than hired labor to distribute feed, and to the reduced production of biomass resulted from high mortality rates. A low production leads to a reduction of labor as a strategy to reduce costs. Wage equity was ~70% for all treatments. Moura et al. (2016) recorded a wage equity of 100% with net-cage tilapia culture carried out in a reservoir located in the semi-arid region of northeastern Brazil. The low equity of the present study is related to the inequality of the salaries paid to the employees. The salaries shown for the shrimp productions vary according to the level of the position, with the highest salaries being earned by those in charge, followed by the vigilantes and supervisors.

Local consumption of the shrimp was zero because the productions were commercialized mainly in the states of São Paulo, Distrito Federal, Santa Catarina, Pernambuco and Ceará. A value of zero was given for health benefits since all employees depended on the Sistema Único de Saúde – SUS (Brazilian public health system). In light of the dynamics of production and the applied management, only 15% of the employees were receiving education. The permanence of employees in the activity was relatively high despite the productions being reduced to mitigate outbreaks of the white spot syndrome virus (WSSV). Permanence in the activity was perhaps due to the working conditions offered by the company, which provided security to those involved in the production process.

The negative distribution of income observed for the M1 treatment was due to the high costs of production and the inability to generate profits. The compensation of the labor observed for the M2 and M3 treatments represented 48 and 32% of the production costs, respectively. This distribution of income was similar to that observed in Moura et al. (2016), which identified the compensation of labor to be 42% of production costs for net-cage tilapia farming as managed by a cooperative.

The relationship of direct and indirect income and the creation of jobs as a function of the investment by the company was low for all treatments due to a decrease in the number of employees as caused by outbreaks of WSSV, requiring a lower number of stocked ponds along with changes in the management of production to reduce costs. The reduction of employees led to a low social sustainability. On the other hand, the reduced production of shrimp biomass led to a relatively high compensation for the labor in all treatments due to the high labor costs per kilogram of shrimp produced. The indicators that increased social sustainability for the M1 treatment were the compensation of the labor per production, gender inclusion and the proportion of self-employed workers, probably due to the generation of more labor to manage the shrimp ponds with high initial populations.

The M2 and M3 treatments were more economically feasible due to reduced operational costs to manage low initial stocking densities of shrimp, which include lower investments in the acquisition of post larvae, feed, fertilizers and labor. The low economic sustainability of the M1 treatment was related to high values of GR and TOC. These high production costs were related to feed expenses, acquisition of post-larvae, cultivation time and high apparent feed conversion.

The commercialization of any production system must attract revenues that exceed the invested capital. In this context, high operating costs make the maximum net revenue of the production systems unfeasible, requiring an increase in selling prices and / or a reduction in production costs (Valderrama and Engle, 2002; Sanches et al., 2014;

Bezerra, 2017). In the present study, the M1 treatment showed no economic sustainability even with the high selling prices per 1 kilogram of shrimp sold in the state of Rio Grande do Norte in 2016. When compared to the M2 treatment, the TOC of the M3 was higher probably due to the management strategy of using raceways to produce large post-larvae, which would increase production costs and reduce revenues and the benefit-cost ratio.

The M2 and M3 treatments had positive IRR values higher than the basic interest rate - SELIC (13.6% per year), suggesting that this activity is economically feasible when practiced with less intensified productions. The IRR was not observed for the M1 treatment because the profits were negative. The mean IRR values found in the M2 and M3 treatments were higher than those found in Bezerra (2017), which identified an IRR of 21.5% for a scenario of investments without financing for shrimp mariculture in the state of Ceará. The higher IRR observed in the present study may be associated with the high values atypical of commercializing the shrimp production due to the low supply of the product as influenced by WSSV and mortality of the production.

The negative net present value (NPV) of the M1 treatment was due to the accumulated losses from not paying the present value of the future payments, which were discounted at an interest rate of 8.5% per year. The negative NPV of the present study affirms Sanches et al. (2014), which suggested that the high costs of commercial feed is one of the main factors that influences the NPV. Sanches et al. (2013) also suggested that if the difference between the current value of the benefits and the present value of the costs or disbursements were positive, the investment would be considered economically feasible. In the present study, the positive NPV of the M2 and M3 treatments suggested economic feasibility of these management strategies. The profit in M3 was less than that in M2 by approximately 54%, probably due to the high costs of rearing juvenile shrimps in an intermediate nursery phase in covered raceways. In all three treatments, the diversity of products was low due to the cultivation systems being carried out as monoculture. On the other hand, the diversity of markets was high since the productions were traded in several Brazilian states including the state where the shrimps were produced (Rio Grande do Norte), which is the second largest producer in the country.

The M1 treatment showed no positive Payback Period (PP – years) with a cash flow projected for twenty years, since gross revenue was inefficient to balance the operating costs effectively paid and obtain a positive net cash flow. Therefore, the M1 treatment showed no economic feasibility. The PP in M3 was lower than that in M2 perhaps due to a reduced cultivation time that permits a greater number of production cycles per year. The high PP values of the M2 and M3 treatments were probably associated with reduced values of the final shrimp biomass. The reduced harvested biomass showed lower gross revenue, which led to a reduction in profits and consequently a higher PP.

The returnability (RI) and profitability (PI) indices were lower in the M1 treatment than in M2 and M3 treatments given the high total operating costs driven by the higher mean values of the apparent feed conversion. The returnability is directly related to the revenues and costs generated from the cultivation and thus, the economic sustainability depends on the quantity of output and the selling price per unit of output since these values reflect the economic attractiveness of the activity. The profits observed in the M2 and M3 treatments were due to the high values paid per kilogram of harvested shrimp during the research period, of which the values were related to the low supply of shrimp. Commercial shrimp productions yielded 52,119 tons in 2016, a reduction of 25.39% from 2015 due to outbreaks of the WSSV (IBGE, 2016).

The environmental sustainability of the production systems was influenced by the generation of solid wastes, since much of the particulate matter produced in shrimp ponds is an aggregation of chemical products, fertilizers, shrimp feces, undigested food, undesired organisms and detritus (Flaherty et al., 2000; Hall, 2004; Paul and Vogl, 2011). The high rates of sedimentation were probably related to the inputs needed to increase the shrimp biomass and due to the eutrophication of the water, which is typical of marine shrimp production systems.

The dependence of the activity on both water and area combined with the potential for eutrophication and the accumulation of particulate matter were factors that reduced the environmental sustainability for all treatments. These values were higher than those found by Moura et al. (2016) for the environmental sustainability tilapia culture in net-cages in a reservoir in a semi-arid region of Brazil, which recorded a water dependence of 4.69 $m^3.t^{-1}$, space dependence of 0.0141 $m^2.kg^{-1}$, eutrophication potential of 56.95 kg of phosphorus per ton of fish produced and 0.079 kg of particulate matter generated per kilogram of fish produced. The aquaculture of salmon (*Salmo salar*) and mollusks are generally carried out in production systems inserted in a body of water, such as through the use of hoop and lantern cages, and require a small area to produce one tonne of the target organism whereas the cultivation in earthen ponds or large net-cages use a much larger area and lead to a greater water consumption (Boyd et al., 2007; Proença, 2013). Thus, the environmental sustainability of shrimp mariculture in earthen ponds is more influenced by the appropriation of this resource when compared to fish production systems in net-cages.

The values of phosphorus accumulation for the M1 and M2 treatments were lower than those found in Proença (2013), which recorded phosphorus values of 0.0011 per kilogram of tilapia produced in an integrated multi-trophic system with the Amazon river prawn. The lower values of the present study may be associated with the systems being monoculture, as higher values in in the polyculture of two or more species are associated with higher accumulations of residues rich with phosphorus such as feed, feces and remains from dead animals.

The high phosphorus values in the M3 treatment when compared to M1 and M2 may be related to performing an intermediate nursery phase of rearing high stocking densities of shrimp, which requires an intensive use of inputs and fertilizers. The values assigned to herbicide, pesticide and hormone pollution were considered zero since none of these products were used in the systems analyzed in the present study. Thus, these systems were considered as relatively sustainable in the environmental point of view.

Variations were observed for the emission and absorption of greenhouse gases in all treatments. Nitrous oxide (N_2O) was emitted in the M1 and M2 treatments and absorbed in the M3 treatment. Nitrous oxide is typically released in small quantities when compared to other greenhouse gases, but its emission has a greater impact due to having an effect hundreds of times greater per molecule than other gases. Methane CH_4 was emitted from the M2 treatment and was absorbed in the M1 and M3 treatments. Carbon dioxide (CO_2) was absorbed only in the M1 treatment and emitted from the M2 and M3 treatments. Thus, the present study presents no clear pattern for the emission and absorption of greenhouse gases for the these shrimp production systems. Yang et al. (2015) reported that the cultivation of *L. vannamei* in earthen ponds in China was a source of greenhouse gases, emitting large amounts of CH_4 and CO_2 and a reduced amount of N_2O. However, Boyd et al. (2010) mentions that aquaculture ponds can act as sinks for these gases.

MODELING OF THE SUSTAINABILITY

The M2 and M3 treatments showed the most balanced position between the three dimensions of sustainability and received the highest overall sustainability index. It is noteworthy that sustainability must be evaluated from a multi-criteria point of view rather than by a singular vision in a multidimensional space, and should be balanced through a system according to the environmental, social, and economic dimensions of modern aquaculture. The shift of sustainability towards one of the dimensions is always considered as detrimental to the other two, therefore the best sustainability is with an index that best overlaps the three dimensions. Thus, all of the treatments in the present study showed low overall sustainability by having an index far from the center of the triangle generated by the MULINO Mdss.

The M2 and M3 treatments were the most economically sustainable likely due to the lower operating costs that would lead to greater profits. These treatments showed IRRs greater than the interest rates observed in the market, resulting in higher indices of returnability. The M1 treatment was most favorable to the environment and showed a tendency towards the social dimension, having the highest values of sustainability scores generated by the *software* MULINO for these dimensions. The M1 treatment showed moderate social sustainability due to high remuneration of work per unit of production as a reflection of the work required for the intensification level of the production. The greater displacement of the M1 treatment from economic sustainability was associated with higher total operating costs, which led to losses for most of the economic indicators in this treatment.

The methodology that combines matrices or sets of indicators is the most efficient and most used measurement of sustainability in aquaculture and its processes. These indicators allow independent criticisms and evaluation of each element, revealing the limitations and which elements should be improved to obtain a more sustainable system.

This information allows timely and accurate responses to improve the sustainability of the system (Latinopoulos et al., 2012; Almeida, 2013; Rapassó et al., 2015; Ting et al., 2015; Valenti, 2018). Thus, one of the indicators that may have contributed to a lower balance of absolute sustainability in marine shrimp farming in earthen ponds for all treatments of the present study may be associated with the low productivity, which led to increased operational costs per production and caused a reduction of employed labor, factors that were not identified in the production systems before outbreaks of the WSSV. Thus, the sustainability of shrimp farming becomes compromised when carried out despite the presence of WSSV, since it negatively affects the expected productivity of the culture.

5. FINAL CONSIDERATIONS

All treatments of the present study were considered unsustainable when analyzed within the framework of the economic, environmental and social dimensions of sustainability. The M1 treatment (high density of shrimp) presented low economic sustainability due to the high mortality and the reduced mean individual biomass of the shrimps at the end of the experimental period. The reduced biomass of the M1 treatment was likely caused by the WSSV, which provoked a reduction in the cultivation time to obtain adequate survival. The M2 (low density of shrimp) and M3 (high density of shrimp, with an intermediate nursery phase) treatments presented higher economic sustainability due to the low employment, lower costs for obtaining post-larvae and feeds, leading to an overall reduction in total operating costs. However, due to the low job creation and the high sedimentation rates of nutrients generated by shrimp mortality from the WSSV, the sustainability of these treatments showed a notable displacement from the social and environmental dimensions.

The shrimp monoculture carried out with high initial densities (M1) and subjected to the WSSV appears to be economically unfeasible since a payback period was unattainable. Shrimp farming practiced with low stocking densities in the presence of WSSV, such as the M2 and M3 treatments, may be economically feasible when carried out with reduced employment and income, leading to negative impacts on social equity and the environment. It is noteworthy that the high prices paid per kilogram of shrimp during 2016 increased the economic sustainability of the M2 and M3 treatments, especially when considering the prices paid in the years 2014 and 2015 would make these two treatments economically unfeasible. The selling prices before 2016 reflected productions unaffected by WSSV. In general, the set of indicators used in the present study was adequate to evaluate the sustainability of shrimp mariculture in ponds and was able to reflect the main strengths and weaknesses of the various management strategies and densities. The DPSIR model evaluated the sustainability of the production systems and identified the most important indicators for the system, as well as provided a holistic view of sustainability of the three dimensions analyzed.

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SUSTAINABILITY OF FARMING NILE TILAPIA IN NET-CAGES IN A RESERVOIR OF THE BRAZILIAN SEMI-ARID REGION

ABSTRACT: The present study evaluated the social, economic and environmental sustainability of a net-cage tilapia farming system located in a reservoir of the semi-arid northeast region of Brazil. The three dimensions of sustainability were evaluated through a set of 35 indicators. Two cultivation with stocking densities of 100 and 125 fish/m² were observed. The Internal Rates of Return were below the Minimum Attractive Rates of Return and Net Present Value indicator was negative for both cultivation systems, showed no attractive financial benefits and no capital return that is capable of generating sufficient annual profits and revenues to keep the system in operation over time. The activity improved the local food supply and quality of animal protein in the state where the enterprise is carried out. Compensation of labor represented 22 and 24% of the production costs with 125 and 100 fish/m², respectively. Various age groups and races were represented among the employees, but the enterprise was operated only by men. The production systems showed reduced environmental sustainability. Phosphorus accumulations were 2.1 and 2.0 kg/tonne for the density of 125 fish/m² and 100 fish/m², respectively, and particulate material accumulations 110 and 100 kg/tonne in 125 and 100 fish/m², respectively. It is noteworthy that the prolonged drought conditions of this semi-arid region may further compromise the low environmental sustainability, and consequently the economic and social sustainability of the fish farming activity in reservoirs of this region.

Key-words: Indicators of Sustainability, Aquaculture, Fish Farming, Environmental impact

1 INTRODUCTION

Per capita fish consumption is predicted to increase worldwide, with expressive growth in Brazil, Peru, Chile, China and Mexico (FAO, 2016). It is estimated that 19 million people work in the aquaculture industry, most of which is centered in Asia, the Caribbean, and Central and South American countries (FAO, 2018a). Specifically in Brazil, it is estimated that aquaculture will be increased by 32% by 2030, with a production of 800 thousand tons (FAO, 2020). In this context, and based on the 2030 Agenda for Sustainable Development (UN, 2015), modern aquaculture must contribute to people's food security, sustainable water management, by reducing the discharge of effluents and chemicals and the increasing the efficiency of water use, promoting inclusive economic growth and establishing sustainable production standards. Advancements in Brazilian aquaculture are due to large investments in the sector over recent years and the creation of public policies that promote participation in the activity (Bueno, et al, 2015). The increase in aquaculture production worldwide is due to the rising demand for healthy and nutritionally adequate foods. Therefore, the sector must adapt to an ever-increasing global fish consumption by generating alternative products and higher yields while improving management strategies, production techniques, and the efficiency of using natural resources (Dantas et al., 2020; Nobile et al, 2019).

Tilapia is a group of species of ciclid fish that has been increasly used in producing fish protein for human food with global production estimated at 5.9 million in 2016 (FAO, 2018b). Currently, Nile tilapia (*Oreochromis niloticus*) is the principal species farmed in the Brazilian aquaculture. Tilapia production in 2019 in Brazil was 432,000 t (57% of national production), which makes Brazil the 4th largest world producer of this species, behind only China, Indonesia and Egypt (PEIXE BR, 2020). Production in net-cages is the major system for tilapia farming in Brazil, mainly in reservoirs (Demétrio, 2012; Araújo et al., 2017; Lima et al, 2018; Chaves et al., 2020). This farm system emerged in the early 2000s with support from Brazilian government programs (Garcia et al., 2014; Bueno et al, 2015; Padial et al, 2017).

The intensive culture of Nile tilapia in net-cages requires a high amount of inputs (Venturoti et al, 2015; Degefu et al, 2019; Bessa et al, in press), which decrease the environmental sustainability of the activity by causing eutrophication and the possible introduction of an exotic species in the natural environment (Gorlac-Lira et al., 2013; Lima Junior, et al, 2018; Yuan et al, 2017; Henry-Silva et al, 2019). Nevertheless, the implementation of Nile tilapia net-cage culture in reservoirs in the semi-arid northeast region of Brazil led to the creation of employment opportunities and improvements in the quality of life of several families (FAO, 2017; Lopes et al, 2017).

Aquaculture production systems should be assessed and compared to each other based on the different aspects of sustainability (Moura et al., 2016; Milewski and Smith, 2019; Nobile et al, 2019). There is great interest to develop sustainable systems and several methods have been established to measure sustainability (O'Higgin, 2019). However, the use of these systems in aquaculture is still incipient. Analyses regarding the sustainability of aquaculture activities include the emergy analysis (Garcia et al., 2014), ecological footprint (Galli et al., 2016; Chang et al., 2017), life cycle analysis (Pahri et al., 2015), resilience analysis (Kluger et al., 2017), and the use of a set of indicators (Boyd et al. 2007; Kruse et al., 2009; Nobre et al., 2010; Rey-Valette et al., 2010; Moura et al., 2016; Valenti et al., 2018). Sets of indicators can be understood as a measure of a component of the system, from which conclusions about a certain phenomenon can be inferred (Heink and Kowarik, 2010). Given the importance of understanding the sustainability of fish production in cages and the development of effective analytical methods, the present study evaluated the environmental, social and economic dimensions of sustainability of a net-cage tilapia production system in a reservoir in the semi-arid northeast region of Brazil.

MATERIALS AND METHODS

The present study was carried out at a Nile tilapia farming cooperative in the Umari reservoir, located in the Brazilian semiarid (5 °42'13”S and 37 °15'18”W) (Figure 1). The fish were reared in net-cages and managed by 13 entrepreneurs that formed the cooperative. The reservoir has an area of 2,923 ha and a maximum capacity of ~293 million m³ (ANA, 2007). The local climate is of the BSw´h´ (Köppen) type, characterized by a very hot and semi-arid climate and with the rainy season occurring in late autumn. During the experimental period, the percentage of reservoir volume in relation to its maximum volume ranged from 19% to 21%.

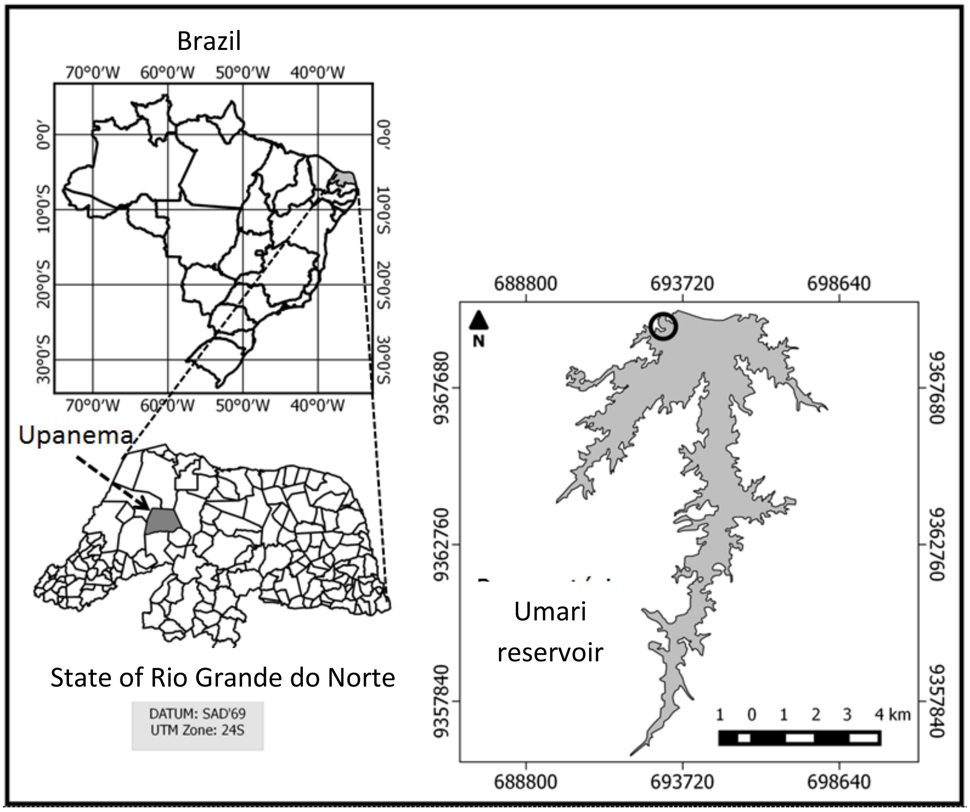

Figure 1. Location of the Umari reservoir in Brazil (5°42’13”S and 37°15’18”W). The circle indicates the area of the reservoir where the Nile tilapia are farmed in net-cages.

The cooperative of the Umari reservoir was visited each month from October 2015 to January 2016 during a tilapia production cycle, from stocking to harvest. Juveniles of

Oreochromis niloticus (118.5 ± 5 g), previously nursed for two months, were stocked in 6 m³ net-cages for two months at 100 and 125 fish/m^3, totaling four months (two months of pre-fattening and two months of fattening, which occurred simultaneously). Four randomly selected net-cages of each density were analysed in the present study. Fish were measured and weighted biweekly and the net-cages were monitored daily for mortality. The evaluation of environmental, social and economic sustainability was performed based on three production cycles by year. The biomass of the fish in the net-cages was estimated biweekly by weighing 5% of the fish sampled in each net-cage. After harvesting, the fish were counted and wighted. Then, the final average mass, survival, and apparent feed conversion ratio were calculated.

Economic Dimension

A set of nine indicators was used to evaluate the economic sustainability. The indicators represented four main aspects of economic sustainability: efficiency in the use of financial resources and the ability to generate capital for reinvestment (Valenti et al., 2018). The economic analyses were based on data provided by the cooperative and on-site observations. The financial movement consisted of information for the years 2012 and 2015. All equipment, utensils, inputs and management used in production were surveyed. Cost-return and cash flow analyses were performed (Engle, 2010). The initial investment included the net-cages, canoe, mass balance, management platform, sheds and some other items of low cost. Externalities were not comprised. Revenues were reported by the cooperative based on sales in 2015 and estimated for the production carried out by the 13 farmers . All monetary amounts were converted from Brazilian Reals to US Dollars and were based on the average trading price from November 2015 to January 2016 (US$ 1.00 = R$ 4.02). Net revenue was calculated considering productivity and an average selling price of US$ 1.24/kg. Profit was calculated as the difference between net revenue and production costs, including taxes.

Environmental Dimension

A set of nine indicators was used to evaluate environmental sustainability (Table 2). They reflect the use of natural resources, the efficiency in using resources, the release of pollutants, and the risk of damaging genetic diversity and biodiversity (Valenti et al., 2018). The nutrients generated from the aquaculture activity was quantified each month by placing sedimentation chambers (in duplicate) under each net-cage, which remained submerged for 24 hours. Each sediment sample was weighed and the concentrations of particulate and organic matter were calculated according to Buffon et al. (2009). The natural sedimentation rate of the reservoir was estimated by placing sedimentation chambers in an area located about 200 m from the net-cages (control). The concentrations of total phosphorus (Koroleff, 1983) and total nitrogen Kjeldahl (AOAC, 2005) were calculated by subtracting the natural sedimentation (control) from the sedimentation recorded below the net-cages.

Social Dimension

Social sustainability was evaluated using a set of 17 indicators (Table 1). They represent four main aspects of the social dimension: social equity, income distribution, equal opportunities, and the generation of jobs and benefits for local communities (Valenti et al., 2018). Data were acquired by interviewing employees of the Umari cooperative with the use of a semi-structured questionnaire (Valenti et al, 2018). In addition, other data were acquired from a survey carried out with the public agencies, i. e., the Brazilian Institute of Geography and Statistics (IBGE-Instituto Brasileiro de Geografia e Estatistica) and the Ministry of Fisheries and Aquaculture.

Table 1. Indicators of economic, environmental and social sustainability.

	Indicators of Sustainability		
	Economic Dimension	Environmental Dimension	Social Dimension
1	Ratio between Net Income and Initial Investment	Use of Space	Pay Equality
2	Internal Rate of Return	Dependency of Water	Proportional Cost of Work
3	Benefit-Cost Ratio	Proportion of Renewable Energy	Remuneration of Work per Unit of Production
4	Net Present Value	General Chemical Pollution	Racial Inclusion
5	Net Profit	Pollution by Hormones	Gender Inclusion
6	Risk Rate	Accumulation of Phosphorus	Age Inclusion
7	Diversity of Products	Accumulation of Organic Material	Required Work per Unit of Occupied Area
8	Diversity of Markets	Accumulation of Particulate Material	Required Work per Unity of Production
9	Invested Capital Generated in the Activity	Risk of Farmed Species	Proportion of Self-Employed

10	Use of Local Workers
11	Income fixation in the local economy
12	Local Consumption of Production
13	Access to Health-Insurance Programs
14	Schooling
15	Permanence in the Activity
16	Participation in Outside Community Activities
17	Safety at Workplace

RESULTS

In both stocking densities, survival was 90% and the Apparent Feed Conversion Ratio was 1.5. Mean final weight was 316.9 grams and 358.8 grams at stocking densities of 125 and 100 fish/m^3, respectively. All investments to implement the net-cage production system was carried out by the 13 members of the Umari reservoir cooperative. The initial investments included 37 net-cages for each member (total of 481 net tanks), canoes, management platform, shed for production and employee support, electronic scale and other items of low cost, totaling US$ 93,445. No reinvestments were made for new net-cages since the environmental licenses prohibited the use of over 37 cages per producer. Furthermore, the compensation of the entrepreneur was considered zero, since members of the cooperative work on other activities and decide individually where they will apply the profits from the farming activity.

The economic sustainability indicators showed that the production system carried out with a stocking density of 125 fish/m^2 was not economically feasible because the Internal Rate of Return (7%) was lower than the Minimum Attractive Rate of Return (10%). The negative Net Present Value (US$ -26619.70) also showed the system as economically unfeasible. The production system with 100 fish/m^2 generated an Internal Rate of Return (5%) and a negative Net Present Value (US$ -47821.30), demonstrating that this system was not economically feasible as well (Table 2). The benefit/cost ratio indicated that for every US$ 1.00 invested in the activity, only US$ 0.69 and US$ 0.44 were transformed into economic benefits for the cooperative with the stocking densities of 125 and 100 fish/m², respectively. The relationship between average annual income and investment was relatively low (<US$ 1.00) for both stocking densities. The annual profit indicator was considered economically satisfactory, but the profit becomes very small and unsatisfactory when this value is divided among the 13 members. The producers used the profit to compensate for loss from mortality, administration of the production, control of inputs and sales. As such, the profit became lower than the minimum monthly wage.

The economic indicator Risk Ratio consisted of 11 factors that increase the risks of negative impacts on aquaculture. In presente stydy, this indicator was of 18% for both stocking densities. Only two of the 11 items were identified: (i) lack of a business plan during the planning stage and (ii) institutional instability, due to changes in regulations and in agencies of promotion and inspection. The cooperative generated only two types of products, of which were whole fish (~98% of total production) and fillets (~2%). The cooperative was focused on three markets of intermediaries, slaughterhouses of the state of Rio Grande do Norte, and small merchants in the city of Upanema/RN and the surrounding region near the Umari reservoir. The capital generated for reinvestment in the activity was considered zero since the environmental licenses permitted a maximum of 37 net-cages per producer (Table 2).

Table 2. Values obtained for the indicators of economic sustainability for the cultivation of Nile tilapia in net-cages in the Umari reservoir for the densities of 125 and 100 fish/m².

Economic Indicators	125 fish/m²	100 fish/m²
1. Ratio between Net Income and Initial Investment (US$)	0.20	0.13
2. Internal Rate of Return (%)	7	5
3. Benefit-Cost Ratio	0.69	0.44
4. Net Present Value (US$)	-26619.70	-47821.30
5. Net Profit (US$)	20383.35	12974.55
6. Risk Rate (%)	18	18
7. Diversity of Products	2	2
8. Diversity of Markets	3	3
9. Invested Capital Generated in the Activity	0.00	0.00

The work required to carry out the cultivation in the Umari reservoir was 2 man-hours-year per square meter (MHY/m²) for both stocking densities, with no variation because the number of workers, hours of work per day and the size of the production area were the same (Table 3). The required work per unit of production was 0.13 and 0.15 man-hours per kg of fish produced (MH/kg) for the densities of 125 and 100 fish/m², respectively. The pay equity was 80% for both treatments. Values of racial inclusion (75%), gender inclusion (52%) and age inclusion (41%) were equal for both densities as well when considering that the composition of the employees was the same between treatments. The indicator income fixation in the local economy showed that only 2 and 3% of the acquisitions of goods were made in the municipality for the densities of 125 and 100 fish/m², respectively, and the other acquisitions were made in other municipalities or states. Local consumption indicated that only 10% of the fish was commercialized and consumed in the municipality through small merchants.

The cooperative offered no health program to its employees and the education level showed that only 7% of the employees were in school while the other 93% had complete or incomplete basic education. In addition, permanence in the enterprise was three years for each employee. Regarding the participation of the employees in community activities, it was shown that 100% of employees had ties with the rural workers union of the city of Upanema/RN. Among the work safety items, the enterprise showed 87% of equipment and actions necessary to carry out the activity with proper safety. Only the use of pigmented gloves and the use of equipment by qualified professionals were not identified.

Table 3. Values obtained for the indicators of social sustainability for the cultivation of Nile tilapia in net-cages in the Umari reservoir for the densities of 125 and 100 fish/m². Labor/unit: Labor per unit.

Indicators of Social Sustainability	125 fish/m²	100 fish/m²
1. Pay Equality (%)	80	80
2. Proportional Cost of Work (%)	22	24
3. Remuneration of Work per Unit of Production (US$/kg)	0.25	0.28
4. Racial Inclusion (%)	75	75
5. Gender Inclusion (%)	52	52
6. Age Inclusion (%)	41	41
7. Required Work per Unit of Occupied Area (hha/m²)	2	2
8. Required Work per Unity of Production (hh/kg)	0.13	0.15
9. Proportion of Self-Employed (%)	0	0
10. Use of Local Workers (%)	100	100
11. Income fixation in the local economy (%)	2	3
12. Local Consumption of Production (%)	10	10
13. Access to Health-Insurance Programs (%)	0	0
14. Schooling (%)	7	7
15. Permanence in the Activity (years)	3.00	3.00

16. Participation in Outside Community Activities (%)	100	100
17. Safety at Workplace (%)	87	87

The indicators of environmental sustainability showed a low dependence on water use and space for both stocking densities of 125 and 100 fish/m². The higher stocking density used an area of 0.27 m² per kilogram of fish produced and a volume of 4.5 m³ per tonne of fish, whereas the lower density used an area of 0.29 m² per kilogram of fish and a volume of 4.5 m³ per tonne of fish (Table 4). Phosphorus accumulation was 0.0021 kg and 0.0020 kg of phosphorus per kilogram of fish for the stocking densities of 125 and 100 fish/m², respectively. Regarding pollution from herbicides, pesticides and hormones, the value was zero as none of these products were used in the studied system.The production system generated 106 kg and 101 kg of particulate material per tonn of fish produced for the densities of 125 and 100 fish/m², respectively. For both densities, approximately 90% of this emission consisted of organic matter (Table 4).

Table 4. Values obtained for the indicators of environmental sustainability for the cultivation of Nile tilapia in net-cages in the Umari reservoir for the densities of 125 and 100 fish/m².

Indicators of Environmental Sustainability	125 fish/m²	100 fish/m²
1. Use of Space (m²/kg)	0.27	0.29
2. Dependency of Water* (m³/t)	4.5	4.5
3. Proportion of Renewable Energy (%)	0	0
4. General Chemical Pollution (kg/t)	0	0
5. Pollution by Hormones (kg/t)	0	0
6. Accumulation of Phosphorus (kg/t)	2.1	2.0
7. Accumulation of Organic Material (kg/t)	99	89
8. Accumulation of Particulate Material (kg/t)	106	101
9. Risk of Farmed Species	5	5

*Indicator used as described in Boyd et al. (2007)

DISCUSSION

Economic Dimension

The production system with 125 fish/m² in net-cages as carried out by the cooperative of the Umari reservoir was shown to be economically unfeasible according to the indicators. The internal rate of return was below the minimum attractive rate of return (10%). The net present value was negative and benefit-cost ratio US$ 0.69 for every US$ 1.00 of investment. Hence, the production with this density showed no attractive financial benefits and no capital return that is capable of generating sufficient annual profits and revenues to keep the system in operation over time. The system with 100 fish/m² was also economically unfeasible and had a benefit-cost ratio of US$ 0.44 for each US$ 1.00 of investment. Furthermore, this production system showed an internal rate of return which was also lower than the minimum attractive rate of return and the net present value was negative. Indicators of economic sustainability for the production system of the present study showed values that contrasted those recorded in Moura et al. (2016), which showed economic feasibility for a tilapia farming system in net-cages managed by an association. In Moura et al. (2016), the internal rate of return was 52% per yearand the production system presented a positive net present value. In contrast to the production system as managed by a cooperative, the association paid no taxes on the revenue nor the financial obligations and salaries of the employees since they had more autonomy in their productions.

Average profitability was 4.4% per year for the stocking density of 100 fish / m², whereas the profitability was 6.3% per year for 125 fish/m². The higher profitability of the latter density is mainly due to both systems operating with the same 15 employees for the management of the 481 net-cages, thereby having equal costs for labor between the two densities. The annual profitability values obtained by the Umari cooperative for the cultivation of Nile tilapia were lower than profitability values (25.9%) obtained by a private enterprise in the Middle Paranapanema region of rural São Paulo (Brazil) in the past decade. At that time, the company supplied 70% of the fish to the fillet industry and 30% to alternative channels such as fisheries, markets and directly to the consumer (Furlaneto et al., 2010). Values in the present study were also lower than those obtained by an association of fish farmers in the northeast semi-arid region of Brazil, which showed annual profitability of 23% when producing *O. niloticus* in a reservoir using net-cages and was exempt from taxes and economic subsidies (Moura et al., 2016). Nearly all (98%) of fish production in the Umari reservoir was sold as whole fish with a fixed value to intermediaries, slaughterhouses and small merchants in the region. In addition, the production was with taxes and without government subsidies, which reflected in a higher production cost when combined with paying employee salaries and other costs.

The relationship between net income and initial investment showed that the amount invested in the Umari cooperative was not efficiently transformed into income, perhaps due to the low revenue generated from the production, resulting in a low return over the life of the project. The indicator of risk was 18% for both stocking densities in the present study. Of the 11 items used to determine this indicator, only the absence of business plan during the planning phase for implementation and institutional instability were observed, since instability may occur due to changes in environmental laws. On the other hand, this indicator showed that some of the cooperative members had specialized training, which leads to greater security of the production given that the correct management is carried out daily and illnesses are treated with more confidence. The cooperative also showed no conflicts with the local community or non-governmental organizations. The number of products and the available markets were considered adequate for the activity with both stocking densities, showing no reduction in sustainability since all production was sold and met local demand. The capital generated from the activity was zero for both systems, showing no reinvestments for the purchase of new cages or any other equipment during the analyzed period because the environmental licenses granted to the cooperative permitted the use of up to 37 cages per member.

Social Dimension

100% of the workforce directly participating in the production and the employment of security and that the employees were local residents. The pay equity was 80% for both stocking densities. These values were considered satisfactory as most employees worked daily in production management and received equal salaries, of which two employees worked additional night shifts as security and received higher salaries. Furthermore, all employees participated in external activities, such as being members of the rural workers union. On the other hand, the generation of job opportunities was reduced, which decreased the social sustainability for both densities. Thus, the overall number of employees was low according to the amount of work per area and per production for the net-cage tilapia culture system in Umari reservoir.

Despite the activity providing direct employment opportunities and indirect employment for approximately 130 intermediaries and small merchants, the number of individuals that received benefits was low. However, when considering the possibility that each worker represented a family, the generation and distribution of income have more social relevance. It is also noteworthy that the enterprise provided safe working conditions to those involved in the production process as only pigmented gloves and the use of equipment by qualified professionals were absent among the work safety items. In addition to providing security to cooperative employees, the enterprise was socially inclusive by providing opportunities to people with little education. Only one of the 15 employees studied while the others had incomplete elementary or high school education. Various age groups and races were represented among the employees, but the enterprise was operated only by men. The average permanence of employees in the activity was 3.0 years, which is relatively high considering that the cooperative only existed for four years when the present study was carried out. The high permanence in the activity was perhaps due to the social relevance and importance of the activity to the members.

Only 10% of the fish were consumed in the region where the cooperative was implemented and all production was consumed in the state of Rio Grande do Norte. All production consumed within the state suggests that the activity improves the local food supply and quality of animal protein in the state where the enterprise is carried out. The ratio of direct and indirect generation of income to the capital invested in the enterprise was low for both stocking densities. This indicator reflected the reality that cultivation systems carried out in net-cages require little management. The compensation of labor relative to the gross production of the enterprise was less than US$ 0.29 per employee per kilogram of production for both densities. The low compensation influenced other indicators such as access to health programs, which none of the cooperative employees received. The proportional cost of work showed that a reasonable share of the production costs was allocated to pay employees.

Income retained in the local community is among the more important indicators of social sustainability. The low retention is due to the purchases of major inputs (including feed and fingerlings) from other municipalities and states, minimalizing local purchases to basic maintenance items from local retail, as well as occasional lodging for some members, fuel, ice and other items of low impact on the local economy. However, local retention of income becomes 90% on the state level, showing that minimal financial resources are destined to other states. Moura et al. (2016) also showed that the profit generated by the activity was destined toward expenditures outside of the community where the enterprise was inserted, which reduced the capacity of the enterprise to provide social and economic development locally.

Environmental Dimension

The indicators showed low dependence on water and space for both densities. Tilapia production in net-cages requires less water volume and space when compared to other aquaculture systems (Boyd, 2005). Problems related to the environmental sustainability of production systems are associated more with the generation of wastes, pollution and the introduction of exotic species than they are with the appropriation of water resources. Verdegem and Bosma (2009) suggested that global aquaculture production can be tripled without increasing water use and dependence. Therefore, expansion of aquaculture activities should be done within the scope of more efficient technologies that reduce organic wastes and escapes of cultivated organisms, and greater conversion of nutrients into harvested fish biomass without increasing the use of water resources.

The value of pollution by herbicides, pesticides and hormones in the present study was considered zero as none of these products were used, giving a positive externality of these production in an environmental point of view. On the other hand, the production systems of the present study showed reduced environmental sustainability due to accumulations of phosphorus (2.1 and 2.0 kg/tonne), particulate material (110 and 100 kg/tonne) and organic material (99 and 89 kg/tonne) at densities of 125 and 100 fish / m^2, respectively. Moura et al. (2016) reported that phosphorus accumulated in the sediment at 0.9 kg of phosphorus per tonne of fish produced for tilapia cultivation in net-cages in a reservoir of the same region. The increased release of phosphorus is among the most detrimental impacts of fish farming since this nutrient promotes eutrophication in aquatic environments, leading to financial and environmental damages. Eutrophication harms producers by causing harmful algal blooms that deplete oxygen and may lead to fish mortality (Lucena-Silva et al., 2019; Leite and Becker, 2019). In addition, eutrophication can pose public health problems since algal blooms include harmful cyanobacteria (Guildford et al., 2003).

The continuous release of solid waste to the environment from the production systems increased the nitrogen and total phosphorus concentrations in the sediment below the net-cages and adjacent areas. The accumulation of nutrients from suspended solids over time can have significant impacts on the environment when considering that most of the waste generated was organic matter. Changes in the bottom sediments from the accumulation of suspended solids can be perceived in the surrounding environment beyond the cultivation area as observed in Huang et al. (2012) and Guo and Li (2003). In general, the present study showed that environmental sustainability was strongly influenced by the generation of solid wastes, of which its increase over time reduced the sustainability of the production system carried out with either density. Azevedo et al.

(2011) reported 200 kg of solid wastes for each tonne of fish produced, nearly double the rate of that found in the present study for both densities.

It is important to note that the semi-arid northeast region of Brazil has experienced prolonged drought between 2012 and 2017, with several locations within the region recording rainfall below the historical average. The current drought conditions of this region have led to drastic reductions of water levels in reservoirs. Furthermore, future climate projections for the area show a gradual increase in temperature and less rainfall (Marengo et al, 2016). Reduced rainfall has been recorded in the state of Rio Grande do Norte over recent years, more specifically in the hydrographic basin of the Apodi-Mossoró river, where the Umari reservoir is located. At the end of 2016, about 70% of the reservoirs in the state that have a water capacity above 5,000,000 m^3 were practically dry (<1% of total volume). The Umari reservoir was with 18% of its total volume at the beginning of 2016 and at the beginning of 2017, the proportion was reduced to 8.8% of the total volume (SEMARH, 2017). As a result, fish farming in net-cages in the Umari reservoir was suspended indefinitely (Henry-Silva et al, 2019). Therefore, the sustainability of fish farming in net-cages as carried out in this semi-arid region must consider the hydrological characteristics of the reservoirs since variations in their water level can drastically reduce the sustainability of this activity.

CONCLUSION

The net-cage production systems of Nile tilapia carried out in the Umari reservoir were economically unfeasible. The majority of the reservoirs in the semi-arid northeastern region of Brazil are subject to high variations in water volume due to prolonged periods of low rainfall (<700 mm/year). Thus, the low environmental sustainability of intensive fish farming in net-cages when carried out in the Umari reservoir with a reduced volume may compromise the economic and social sustainability of the activity, especially in periods of prolonged drought. Water availability for this activity should also be taken into consideration when defining the sustainability of net-cage fish farming carried out in reservoirs of the semi-arid northeast region of Brazil. This region has thousands of artificial reservoirs, which is more than any other semi-arid region around the world. However, this region is susceptible to long periods of drought that compromise the use of the reservoirs.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed by the authors.

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EMISSÃO DOS GASES DO EFEITO ESTUFA: ASPECTOS TEÓRICOS E METODOLÓGICOS TENDO COMO FOCO A AQUICULTURA

INTRODUÇÃO

A emissão de gases que contribuem para o aquecimento global pode ocasionar efeitos negativos ao meio ambiente e a sua biodiversidade, além de prejuízos à própria qualidade de vida do ser humano. Diversas atividades antrópicas contribuem para a emissão destes gases e influenciam diretamente as mudanças climáticas mundiais (OLIVEIRA, 2015; LARMINAT, 2016; MAPATO & WANAPT, 2017, ROJAS-DOWNING et al., 2017). Uma importante fonte antrópica de gases do efeito estufa provém da queima de combustíveis fósseis, que libera o dióxido de carbono (CO_2). Entre as fontes de outros gases, podemos citar os fertilizantes utilizados na agricultura e na pecuária, que liberam óxido nitroso (N_2O), a produção de gás e petróleo, cultura de arroz e os processos digestivos de ruminantes que emitem metano (CH_4) (CONRAD, 1999; PUROHIT e AGRAWAL, 2004; KUMAR, 2013; KUMAR et al., 2013).

Entre os gases do efeito estufa, o mais emitido para a atmosfera é o CO_2, que é responsável por mais de 60% das emissões (RAY et al, 2019). Por sua vez, a quantidade de CH_4 e N_2O emitida para a atmosfera é, respectivamente, 18% e 6%, bem menor quando comparada à quantidade de CO_2, mas o potencial de aquecimento, respectivamente, é de 23 e 298 vezes maior que o CO_2 (SCHOTT, 2016; CERRI et al., 2007). De acordo com os relatórios do IPCC (2016) a concentração de dióxido de carbono sofreu um grande acréscimo de 1750 até 2015, onde que foi verificado um aumento do nível de CO_2 atmosférico, passando de uma concentração de 280 ppm para 400 ppm, ultrapassando as taxas naturais dos últimos 650 anos (180 a 300 ppm). Pesquisas têm demonstrado que atemperatura média do planeta já aumentou em torno de 0,3-0,6° C, desde o início deste século devido a esse fenômeno, e indicam no do próximo século a temperatura global deverá aumentar novamente, podendo aumentar de 1 a 3° C a temperatura atual (MARCELINO et al., 2015; SAMUEL-FITWI et al., 2012; YANG et al., 2014).

As mudanças no padrão de uso da terra também interferem nas fontes e sumidouros de gases do efeito estufa (RAY et al, 2019, SCHOTT et al., 2016; YANG et al., 2012; COLE et al. 2007). As emissões de gases de efeito estufa liberadas pelas atividades agropecuárias aumentaram praticamente 45% desde 1990, atingindo 440 milhões de toneladas de equivalentes de carbono em 2012 (IPCC, 2016, Kumar et al

2013). Somando esse volume às emissões de energia, mudança no uso da terra, aumento do confinamento de lavouras e resíduos, também associado às atividades agrícolas, o setor de agronegócio agora responde por cerca de 60% do total de emissões brasileiras (IPCC, 2016; MCTI, 2013). Além dos efeitos diretos da elevação da temperatura sobre os organismos, o aquecimento global poderá também afetar a produção pela redução da produtividade, assim como pelo favorecimento a maior incidência de pragas doenças devido às mudanças bruscas de ambiente (FERNANDES e FERNANDES, 2008).

Os animais criados em cativeiro e seus subprodutos são responsáveis por cerca de 50% das emissões de gases de estufa liberados para atmosfera (GOODLAND, 2009). Os gases de maior relevância produzidos por estes processos, em termos de quantidade e potencial de efeito estufa, são o dióxido de carbono (CO_2), o metano (CH_4) e o óxido nitroso (N_2O) que comprovadamente interagem com a radiação infravermelha na atmosfera causando a intensificação do efeito estufa natural e influenciando para as alterações climáticas globais (MARCELINO et al., 2015; WANG et al., 2019; RAY et al, 2019). Entre os sistemas de produção animal em confinamento, a aquicultura tem se destacado, apresentando-se como uma forma eficiente de produção de proteína de origem animal para alimentar a crescente população mundial que se desenvolve, principalmente por apresentar diversas vantagens em relação a outras atividades, como por exemplo, curtos ciclos de produção, elevado nível tecnológico e demanda de pequeno espaço para produção (FAO, 2016; FAO, 2020). Apesar de constituir uma atividade influenciada pelas mudanças climáticas, a aquicultura também pode colaborar para o efeito estufa através dos processos básicos que ocorrem no sistema sedimento-água-animais, podendo atuar como fonte ou dreno destes gases dependendo das práticas de manejo utilizadas, dependendo da intensidade de estocagem dos organismos, do manejo alimentar e das características bióticas e abióticas do ambiente aquático onde é realizado o cultivo dos organismos (SOARES & HENRY-SILVA, 2019).

FLUXO DE GASES DOS EFEITO ESTUFA EM AMBIENTES AQUÁTICOS

Os ecossistemas aquáticos podem ser fontes significativas de emissão de gases que contribuem para o efeito estufa (DEAN & GORHAM, 1998; COLE et al. 2007; ENRICH-PRAST & PINHO, 2008; SILVA et al, 2016). A maior parte dos dados que dá subsídio a essa informação baseia-se em estudos realizados em rios, lagos e principalmente em reservatórios de hidrelétricas, sendo relativamente reduzidas as informações sobre o fluxo de gases em ambientes aquáticos utilizados para criação de organismos aquáticos (LINKHORST et al., 2020; SANCHES et al., 2019; BERGEN et al., 2019; ALMEIDA et al, 2016; SOARES & HENRY-SILVA, 2019; MARCELINO et al, 2015; CAILLEAUD et al, 2014; DESHMUKH, 2013; BASTVIKEN et al, 2011; SBRISSIA et al, 2011).

Os gases do efeito estufa geralmente são gerados no sedimento dos ambientes aquáticos e, inicialmente, ficam dissolvidos na água (CARDOSO et al., 2019, PRAIRIE et al., 2018). O metano, por exemplo, tende a ser formado por bactérias metanogênicas em zonas sem oxigênio, geralmente em áreas mais profundas (ZINDER, 1993; SCHINK, 1997). O metano e o óxido nitroso, que são menos solúveis que o dióxido de carbono, se agregam em forma de bolhas, sendo que estas bolhas não conseguem mais ficar retidas no sedimento e, então, se soltam e migram para a superfície da água (CAO et al, 1996). O dióxido de carbono tende a ficar retido na água porque é mais solúvel, mas uma fração pequena entra nas bolhas. Nem todo metano gerado no sedimento é liberado em forma de bolhas. Em águas rasas, parte do metano se difunde até a superfície. Geralmente, em profundidades maiores, todo metano presente pode ser emitido através do processo de difusão porque a pressão da coluna de água não possibilita a formação de bolhas. Como nas camadas superficiais da coluna d´água a concentração de oxigênio aumenta, as bactérias presentes podem produzir dióxido de carbono a partir do metano e oxigênio. Então, a camada oxigenada do ambiente funciona como sumidouro de metano, da mesma forma que a fotossíntese é um sumidouro para o dióxido de carbono (SANTOS et al., 2005).

Os principais fatores que podem influenciar na emissão de gases do efeito estufa nos ambientes aquáticos são a quantidade de matéria orgânica presente na água ou no sedimento, profundidade da coluna d’água, a temperatura, o clima, a quantidade de biomassa submersa, a natureza da vegetação e da área alagada e a idade do ambiente aquático (MARTIN & MCCUTCHEON, 1999). Estes fatores também têm grande influência na produção primária dos ecossistemas aquáticos, havendo uma tendência de correlação positiva do fluxo de gases do efeito estufa com o seu estado trófico (MARTIKAINEM, 2002; SVENSSON, 2005).

LIMA et al. (2005), ao estudaram o efeito das frentes frias nos parâmetros limnológicos e no fluxo dos gases do efeito estufa, concluíram que a massa de ar fria aumentou a velocidade dos ventos e diminuiu a temperatura da água e, consequentemente, o fluxo dos gases do efeito estufa. Já a emissão média do dióxido de carbono aumentou e o tamanho e a frequência das bolhas de metano diminuíam após a passagem da frente fria. Além disso, a turbidez e a clorofila aumentaram e mantiveram-se elevadas. Ainda segundo os autores, tanto a chuva quanto o vento fornecem oxigênio para o ambiente, possibilitando a conversão do metano para dióxido de carbono pelas bactérias metanotróficas. Acreditava-se que a concentração de dióxido de carbono e o fluxo para a atmosfera diminuiriam, devido ao consumo do dióxido de carbono pela comunidade de fitoplâncton, entretanto, com o aumento da chuva, a concentração de dióxido de carbono também aumentou devido à oxidação do metano. Além disto, houve o aumento da nebulosidade, limitando a quantidade de luz na coluna d´água e consequentemente a produtividade do fitoplâncton.

Áreas localizadas em regiões tropicais tendem a apresentarem taxas de emissão maiores que aquelas situadas em regiões boreais e temperadas (LIMA et al., 2005; SANTOS et al., 2005). Uma possível razão para este fato é que a temperatura da água em regiões tropicais é muito mais alta, consequentemente, a taxa de decomposição da matéria orgânica é maior, elevando o fluxo de emissão do metano e do dióxido de carbono (LOUIS et al., 2000). A idade do ambiente aquático também é considerada um fator importante nas emissões dos gases. Inicialmente, acreditava-se que o total das emissões diminuiria com o tempo, mas outros estudos demonstraram que esses ambientes emitem mais gases em seus primeiros anos de existência (LIMA, 2002; KEMENES et al. 2007, ROLAND, et al 2009). Além disto, as plantas aquáticas e os microrganismos, bem como as características da área inundada, no caso dos reservatórios, também influenciam na capacidade de emissão dos gases do efeito estufa. (LOUIS et al., 2000).

As plantas aquáticas emersas, por exemplo, auxiliam na passagem do metano do sedimento direto para a atmosfera. Por outro lado, as macrófitas aquáticas enraizadas também podem ser importantes na oxidação do metano, pois seu sistema radicular promove a oxigenação do sedimento, permitindo o crescimento de bactérias metanotróficas que oxidam o CH_4 em CO_2 (KING, 1994; FONSECA et al., 2004; MARINHO, 2019). Estudo realizado por Faria et al (2015), constatou que hidrelétricas instaladas ou previstas para serem construídas na Amazônia podem emitir elevadas concentrações de gases do efeito estufa. Os autores estimaram que dezoito novos reservatórios poderão emitir até 21 milhões toneladas de metano e 310 milhões de dióxido de carbono nos próximos 100 anos. Mesmo com a remoção da vegetação da área a ser inundada, a decomposição da matéria orgânica que sobra do corte das árvores e o carbono presente no solo favorece a formação de gás carbônico e metano. Além disto, o rio que foi barrado para a construção da hidrelétrica, continua aportando sedimentos e matéria orgânica para o reservatório.

FLUXO DE GASES DO EFEITO ESTUFA EM ATIVIDADES DE AQUICULTURA

De acordo com a FAO (2020), a produção aquícola em 2018 foi estimada em 82 milhões de toneladas, sendo que a aquicultura continental foi responsável por cerca de 51 milhões de toneladas, ou seja, 62% de toda a produção. A aquicultura é atualmente uma alternativa para atender às crescentes necessidades alimentares do mundo (FAO, 2016), mas enfrenta o desafio de manter lucratividade, alta geração de alimentos, e ao mesmo tempo, ser sustentável, reduzindo os impactos ambientais causados pela produção (HENRY-SILVA et al, 2015; MORAES & HENRY-SILVA, 2018; RAY et al, 2019; CACHO et al., 2020). A alta competitividade e a importância econômica do setor mundialmente, juntamente com o tamanho da área de produção que ocupam, chamam a atenção da comunidade internacional, que exige cada vez mais práticas responsáveis do ponto de vista ambiental e social. Neste contexto, aspectos ambientais, incluindo o impacto nas mudanças climáticas e a quantificação dos fluxos de gases de efeito estufa, ainda constituem uma lacuna que precisam ser melhor estudadas. Portanto, conhecer a dinâmica de emissão de gases gerados e quantificá-los corretamente é essencial para a avaliação da sustentabilidade das atividades de aquicultura (VALENTI, et al., 2018).

Embora a aquicultura seja uma atividade dependente das condições ambientais, ela também é uma atividade potencialmente contribuidora para as mudanças climáticas através da emissão de gases de efeito estufa por meio dos processos básicos que ocorrem no sistema solo-água-animal podendo atuar como fonte ou dreno destes gases dependendo das práticas de manejo utilizadas (SCHOTT et al, 2016; YANG et al, 2012; ORJUELA, 2011; BOYD et al, 2010; ENRICH-PRAST & PINHO, 2008; COLE et al, 2007; SANTOS et al, 2008). Como um emissor, sobretudo, de óxido nitroso (N_2O), a maioria dos estudos envolvendo gases de efeito estufa na aquicultura concentra-se nas emissões desse gás (DATTA, 2009; HU et al, 2012; WILLIAMS & CRUTZEN 2010; SCHNEIDER et al 2005). Em sistemas de aquicultura, o N_2O pode ser produzido durante os processos de nitrificação e desnitrificação microbianas. Os mecanismos exatos de produção N_2O na aquicultura estão relacionados com os parâmetros operacionais específicos, como fertilizações, assim também como as condições ambientais, que podem afetar ambos os processos (KAMPSCHREUR et al., 2009; HU et al., 2013).

A aquicultura, para atender à crescente demanda, vem adotando sistemas intensivos com altas densidades de organismos cultivados. A elevada densidade de estocagem, associada ao aporte de nutrientes e matéria orgânica nos sistemas de cultivo, podem contribuir para as emissões de gases do efeito de estufa para a atmosfera. A indústria da aquicultura se continuar a aumentar sua taxa de crescimento anual, poderá responder por 5,7% das emissões antrópicas de óxido nitroso até 2030 (HU et al., 2012). Soares & Henry-Silva (2019), ao quantificarem o fluxo de gases do efeito estufa (CH_4, CO_2, N_2O) em viveiros de cultivo de camarão marinho *Litopenaeus* vannamei, submetidos a diferentes condições de cultivo sugerem que as condições ambientais e de manejo, constataram que este cultivo atuar como fonte ou drenagem de gases. Os autores concluíram ainda que as emissões foram potencialmente críticas, em relação a N_2O, quando comparadas às emissões de outros sistemas de produção. Por outro lado, o cultivo *L. vannamei*, quando realizado com o uso de fertilizantes orgânicos, como o melaço, apresentou capacidade de absorção potencial de gases como CH_4 e CO_2.

Atualmente cerca 16,6 milhões de toneladas de carbono estão submersos em tanques de aquicultura a nível mundial. Isto é cerca de metade da quantidade observada em lagos naturais e águas interiores (BOYD, 2010). É importante ressaltar, que os impactos variam de acordo com a espécie cultivada e os níveis de intensificação de produção, sendo que o fluxo de gases nos viveiros de aquicultura pode ser influenciado pelas variáveis físicas e químicas da água, como pH, oxigênio dissolvido e temperatura, atividade metabólica da comunidade autotrófica (HU et al, 2012; YANG et al, 2015). Alguns sistemas produtivos, considerados pouco impactantes, podem inclusive oferecer alguns benefícios ambientais, atuando como sumidouro desses gases (VALENTI et al., 2011; 2010). Neste contexto, é imprescindível que se estabeleçam métodos adequados para a quantificação do fluxo de gases do efeito estuda das mais diversas atividades de aquicultura, visando minimizar possíveis impactos ambientais e almejando mudar o paradigma de se avaliar a sustentabilidade destas atividades apenas por meio de indicadores de qualidade de água.

QUANTIFICAÇÃO DO FLUXO DE GASES EM AMBIENTES AQUÁTICOS UTILIZADOS PARA ATIVIDADES DE AQUICULTURA

A liberação dos gases nos ecossistemas aquáticos acontece de duas maneiras, pela emissão difusiva e pela emissão ebulitiva. Além das emissões difusivas e ebulitivas também é possível quantificar as concentrações dos gases no sedimento com o auxílio de um coletor tipo Kajak acoplado a um tubo de acrílico (amostrador tipo “core”), visando a obtenção de amostras sem misturar as camadas do sedimento de viveiros e tanques de aquicultura. A emissão ebulitiva, que ocorre por meio de bolhas que se formam no substrato, tem um papel de destaque, especialmente quando o metano se encontra em altas concentrações no sedimento, ocasionando uma menor possibilidade de oxidação na coluna d’agua (KELLER e STALLARD, 1994; BASTVIKEN et al., 2004). A emissão ebulitiva pode ser quantificada por meio de funis invertidos posicionados cerca de 30 centímetros abaixo da superfície para capturar espontaneamente as bolhas ascendentes. Na ponta do funil é acoplado um frasco para coletar os gases, que posteriormente são analisados em cromatógrafo (PRETO et al., 2015, ANDERSON, 2005; SANTOS et al., 2005).

Na emissão difusiva, os gases dissolvidos na água se expandem para o ar, em um processo semelhante à evaporação da água e sua avaliação em campo é feita através de câmaras de difusão (PRETO et al, 2015, ANDERSON, 2005). A maior parte das câmaras é instalada sobre boias que permite que a câmara flutue sobre a superfície da água. De acordo com ANDERSON (2005) não existe uma norma técnica que especifique como estas câmaras devem ser fabricadas e nem uma norma técnica sobre a metodologia de amostragem. É importante usar na fabricação da câmara um material que não fixe o gás de interesse e que também não seja afetado pela difusão do ambiente. O ar dentro das câmaras deve estar bem espalhado para evitar áreas vazias, particularmente em câmaras retangulares. A metodologia operacional consiste em colocar a parte aberta da câmara sobre a superfície da água, permitindo que emissões da superfície da água se acumulem dentro da câmara. As análises qualitativas e quantitativas dos gases são realizadas em laboratório com cromatógrafos (PRETO et al., 2015, ANDERSON, 2005; SANTOS et al., 2005).

Apesar do avanço da tecnologia para a medição das emissões de gases do efeito estufa não há metodologias especificas disponíveis para a estimativa direta de gases provenientes da atividade de aquicultura. PRETO et al (2015) recomenda o uso do funil invertido para a avaliação do fluxo por ebulição e de câmaras difusivas para a avaliação do fluxo difusivo como padrões de metodologias e indica estas metodologias para novos estudos, mesmo em paralelo com outras técnicas de medição.

MÉTODO DE COLETA DOS GASES DISSOLVIDOS EBULITIVOS E DIFUSIVOS

1. A coleta pode ser feita em qualquer ponto da área amostrada, desde que o mesmo não esteja sendo influenciado por aeradores, vegetação e etc.
2. Aspire 48 ml de água da área a ser amostrada utilizando a seringa.
3. Com a mesma seringa cheia de água, aspire 12 ml de gás nitrogênio.
4. Agite a seringa vigorosamente de forma constante e homogênea por 2 minutos (Figura 1) para dessorver[1] os gases da água para o gás N_2*.

* O gás N_2 é utilizado por ser o gás de arraste no detector de ionização de chamas (cromatógrafo), portanto não possui nenhum contaminante.

Figura 1. Agitando a seringa por 2 minutos com auxílio do cronômetro, em coleta diurna e noturna (Prof. Bohdan Matvienko).

5. Após os 2 minutos de agitação, transfira o ar confinado (*headspace*[2]) da seringa para a ampola gasométrica.
6. Armazene as ampolas em uma estante própria (Figura 2)

Figura 2. Detalhe de estante utilizada para estocagem das ampolas.

[1] Dessorver = liberar os gases dissolvidos na água.

[2] *Headspace* = espaço gasoso no interior da seringa ou ampola gasométrica.

O cálculo da concentração de gases nas amostras de água é realizado de acordo com o processo de *headspace*. O *headspace* é uma técnica excelente e sensível, utilizada para analisar compostos em baixas concentrações. Nesta técnica o analito é necessariamente mais volátil que a matriz, visando sua volatilização preferencial, podendo ser determinado sem os interferentes dos outros componentes da amostra, por meio da análise do vapor desprendido do analito (Soleta, 1989). A principal característica do *headspace* é a possibilidade da determinação de componentes voláteis da amostra a ser estudada de forma direta. Além disso, o *headspace* torna-se insubstituível e muito eficiente, pois possibilita a introdução da amostra sem pré-tratamento no cromatógrafo a gás. Isto torna-se mais crítico principalmente devido à baixa detectabililidade dos detectores cromatográficos e a indesejável contaminação da coluna por resíduos não-voláteis.

A concentração do gás dissolvido na água medido por *headspace*, em mol por litro [M], é dada por:

$$C = p\,F + (p - s)\,v / (VRT)$$

Onde:

C = concentração do gás em questão (ex: CH_4 ou CO_2) dissolvido na água, dado em $mol.L^{-1}$;

p = pressão parcial do gás em questão, medida no *headspace*, dada em ATM;

F é dado pela fórmula: F = 54,847 exp (A + B / T + C ln T + D T + E T^2). As letras de A a E correspondem às constantes que para o metano e gás carbônico são dados na tabela abaixo:

Tabela 1. Constantes de CH_4 e CO_2 utilizadas na equação.

CH_4	CO_2
A = -416,159289	A = -4957,824
B = 15557,563	B = 105288,4
C = 65,255259	C = 933,170
D = -0,0616975729	D = -2,845886
E = 0	E = 0,001480857

T = temperatura em Kelvin;
R = 0,082 [L atm $K^{-1}mol^{-1}$] *;
s = 0 (valor de contaminantes do gás N_2 utilizado nos detectores de condutividade térmica e ionização de chamas).
v = volume do *headspace*, em mL
V = volume da água, em mL

* Constante universal dos gases nas Condições Normais de Temperatura e Pressão (CNTP)

T = K (273^{o})

$$P\ V = n\ R\ T$$

ANÁLISE DOS GASES EBULITIVOS

- Flutuadores (Garrafas tipo pet 2 L);
- Recipiente para armazenagem do gás captado no funil (Garrafa tipo pet 600 mL);
- Tampas de garrafas tipo pet;
- Cola plástica;
- Cerra de cortar plásticos e canos;
- Funil de fibra de vidro ou lona;
- Cordas ou barbantes (resistentes);
- Contrapeso (tijolo ou peso de ferro);
- Bote inflável;

1. Meça o volume exato de água que o recipiente de coleta de gás (Garrafa de 600 mL) comporta até a borda superior (boca da garrafa) do recipiente.

2. Corte a tampa da garrafa com a serra de forma que fique apenas a circunferência onde se encontra a rosca da tampa (Figura 3);

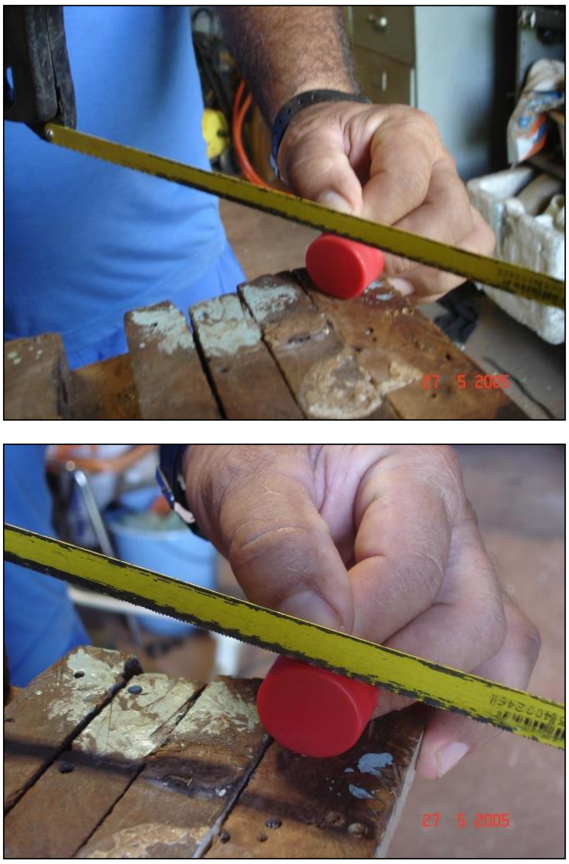

Figura 3. Detalhe da confecção da parte de rosca onde será inserido o recipiente de coleta de gases (Garrafa de 600 mL).

3. Na abertura localizada no vértice do funil fixe a circunferência onde se localiza a rosca da tampa de garrafa tipo pet com cola plástica (Figura 4). Faça esta etapa com muito cuidado para não deixar qualquer abertura que possa permitir a entrada de ar;

Figura 4. Fixação da rosca no vértice do funil com cola plástica.

4. Corte pedaços de barbantes para a amarração dos funis e dos flutuadores dentro da água. Obs: Após o preparo do material siga as etapas abaixo para a realização da coleta.
5. Após a preparação do material é necessário escolher o local onde será realizada a coleta dos gases. É necessário escolher um local (ponto) na área de amostragem onde a movimentação da água é homogênea e representa o sistema hídrico que será avaliado. Se possível instale mais de um funil (no mínimo 3) no viveiro objeto de estudo como repetição da sua amostragem;
6. Vá até o ponto de amostragem com o bote para evitar o contato dos pés com sedimento. O atrito dos pés com o sedimento em locais de baixa profundidade poderia liberar bolhas de gases presos ao sedimento. Isto pode alterar os resultados do trabalho;
7. No ganchinho interno do funil amarre um pedaço de barbante que pode variar de acordo com a profundidade do local a ser amostrado. Na outra extremidade do barbante amarre o objeto que será utilizado como peso. O peso não pode descansar no sedimento para não alterar a liberação de gases para a coluna d’água;
8. Para cada ganchinho localizado na parte externa do funil, também, amarre um pedaço de barbante. Na outra extremidade deste barbante amarre um flutuador (Garrafa tipo pet 2L). Os equipamentos de flutuação e peso deverão ser materiais que não permitem o movimento do funil dentro da área amostrada; o funil deverá ficar submerso, porém nunca tocar o sedimento do local amostrado.
9. Com o peso e os flutuadores presos ao funil, encha completamente o recipiente de coleta de gás com água do local amostrado. Faça esta etapa com muito cuidado, pois não deverá ficar nenhuma bolha dentro do recipiente de coleta de gás. Para tanto, este procedimento deve ser realizado com os equipamentos submersos;
10. Com o recipiente cheio, pegue o funil e o recipiente, coloque-os dentro d’água e enrosque o recipiente na extremidade do funil (vértice) onde se localiza a circunferência com a rosca da tampa. Mantenha os equipamentos submersos;
11. Em seguida coloque o funil com o recipiente voltado para cima e certifique que não há bolhas dentro do recipiente de coleta de gases. Caso haja bolhas repita os procedimentos das etapas 5.6 e 5.7.

12. O funil com o recipiente deverá permanecer no ambiente de amostragem por 24 horas;
13. Após 24 horas de permanência do sistema de coleta por ebulição na área de amostragem é realizada a retirada do recipiente de coleta de gás:
14. Para a retirada do recipiente de coleta de gás deve-se desrosqueá-lo, cuidadosamente para não perder a amostra coletada, e mantê-lo na mesma posição (fundo do recipiente voltado para cima), tampá-lo com uma tampa de garrafa tipo pet intacta (perfeita). Todo este procedimento de retirada do recipiente de coleta de gás deverá ser realizado com os equipamentos submersos;
15. Após tampado o recipiente de coleta de gases pode ser retirado de dentro d'água;
16. Com a amostra no laboratório mede-se o volume de gás coletado pelo volume de água deslocado do recipiente ao longo das 24 horas de coleta.

As concentrações dos gases são obtidas por análise cromatográfica utilizando detector de condutividade térmica e coluna empacotada Hayesep D, que estabelece as concentrações de CH_4, CO_2 e N_2 no gás captado. A partir das concentrações é calculado as taxas de emissão por ebulição expressas em mg C m^{-2} d^{-1} e mg N_2 m^{-2} d^{-1}.

ANÁLISE DE GASES DIFUSIVOS

- Termômetro (Minipa Digital®) e GPS (Garmin 72®)
- Cilindro de cano PVC com volume de 1 L
- Seringa (60 ml) com entrada e saída múltipla (divisor)
- Câmara de difusão*
- Cronômetro
- Ampolas Gasométricas (cilindro provido de pistão) para armazenagem do gás (35 ml)*
- Estante para estocar ampola gasométrica
- Recipiente contendo gás nitrogênio (pode ser uma garrafa pet 2L, dependendo da quantidade amostral).
- Cromatógrafo a gás modelo U-13*
- Canalículos de borracha (tipo utilizado em procedimentos farmacêuticos ou médicos) usados para transferência dos gases coletados;

- Mistura gasosa padrão (Air Liquide®) contendo 11 ppm de metano (CH_4) e 768 ppm de gás carbônico (CO_2).

* Equipamentos fabricados pela Construmaq São Carlos

OBS: Antes de iniciar as coletas é necessário:

1- Conhecer a altitude do local a ser amostrado. Pode ser utilizado o GPS
2- Obter a temperatura do ambiente e do corpo d’água a ser analisado.

1. Primeiramente é necessário escolher um ponto de amostragem onde a movimentação da água é homogênea e seja representativo para o sistema hídrico que será avaliado. Caso o sistema onde será feito a coleta esteja exposto ao vento ou a um sistema de aeração, a coleta pode ser realizada em qualquer ponto.
2. Afunde a câmara de difusão na água até que a mesma esteja completamente cheia de água e sem possibilidade de entrada de ar (Figura 5). A câmara não pode ficar posicionada de maneira que permita a entrada de ar (Figura 6).

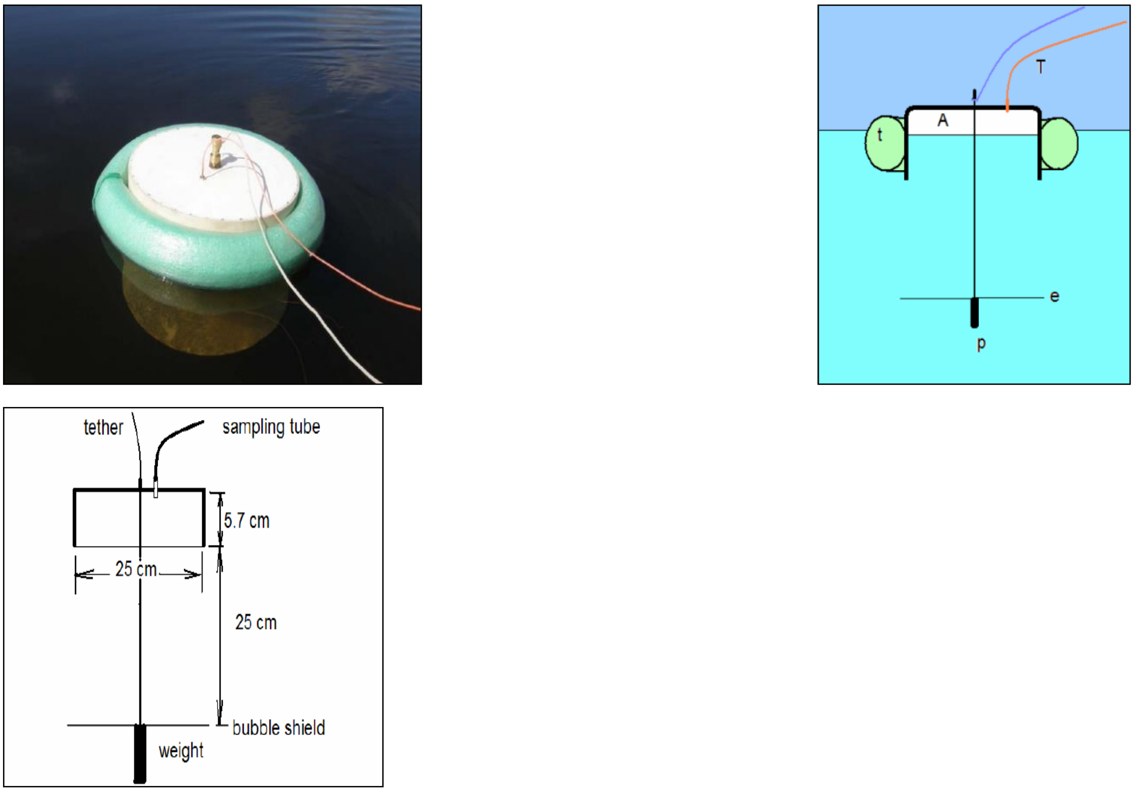

Figura 5. Câmara cheia de água e posicionada de maneira adequada.

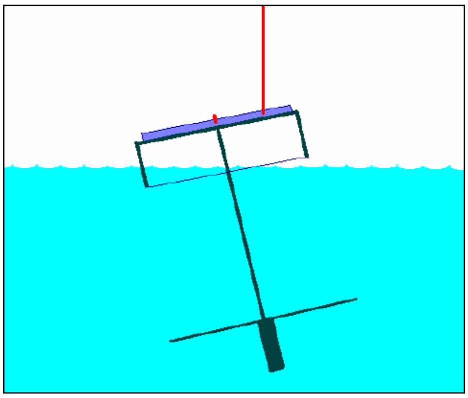

Figura 6. Câmara posicionada de maneira inadequada permitindo a entrada de ar.

3. Remova o ar do interior da seringa aspirando ar de dentro da câmara para dentro da seringa e, em seguida, por meio das saídas múltiplas, expulse o ar da seringa para o ambiente.
4. Para expulsar o ar da seringa, posicione o divisor de saída múltipla de forma que o ar aspirado da câmara seja lançado para fora da seringa. <u>IMPORTANTE:</u> Repita este processo duas vezes para cada amostra a ser recolhida nos diferentes tempos (T0, T1, T2, T4).
5. Afunde o cilindro na água, enchendo-o e, com sua extremidade da abertura voltada para baixo, retire-o da água formando um ângulo de aproximadamente 90 graus entre a superfície da água e o ar. Este movimento fará com que a água saia do cilindro permitindo a entrada de ar. Observação: Procure encher o cilindro com o ar mais próximo da superfície da água (Interface água-ar).
6. Imediatamente após a entrada do ar no cilindro, insira-o verticalmente na água próximo à câmara de difusão. Dentro da água e abaixo da câmara, vire a abertura do cilindro para o interior da câmara, permitindo que o ar do cilindro passe para a câmara de difusão e fique acondicionado em seu interior (Figura 7). Se houver escape do gás do cilindro é necessário repetir o processo desde o início.

Figura 7. Momento em que o ar no interior do cilindro é transferido para o interior da câmara.

7. Imediatamente após a inserção do ar no interior da câmara, com a seringa vazia, aspire o ar confinado no interior da câmara. Esta amostra representa T = 0 (zero). O ar é aspirado da câmara por meio de uma seringa ligada a um canalículo (Figura 8). Na ponta da seringa, um divisor de saída múltipla contendo uma válvula permite que os gases aspirados do interior da câmara sejam transferidos por meio de outro canalículo a uma ampola de vidro (cilindro de vidro com pistão) para armazenamento da amostra (Figura 9). O cronômetro deve ser acionado assim que a primeira amostra for aspirada. Desta forma serão obtidas amostras em quatro intervalos consecutivos:

    - T = 0: imediatamente após a inserção do ar na câmara.
    - T = 1: após 1 minuto;
    - T = 2: após 2 minutos;
    - T = 4: após 4 minutos

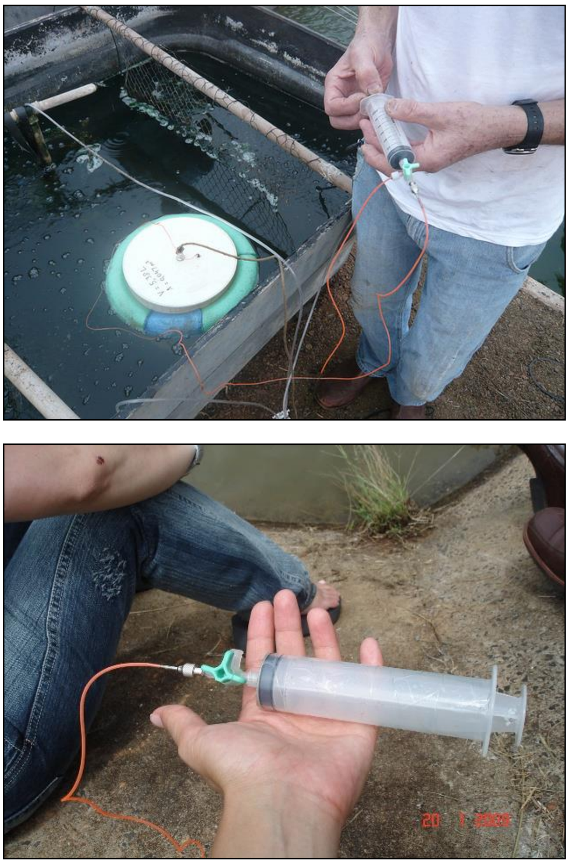

Figura 8. Ar sendo aspirado com auxílio da seringa e dos canalículos de transferência dos gases. Detalhe do divisor múltiplo na ponta da seringa.

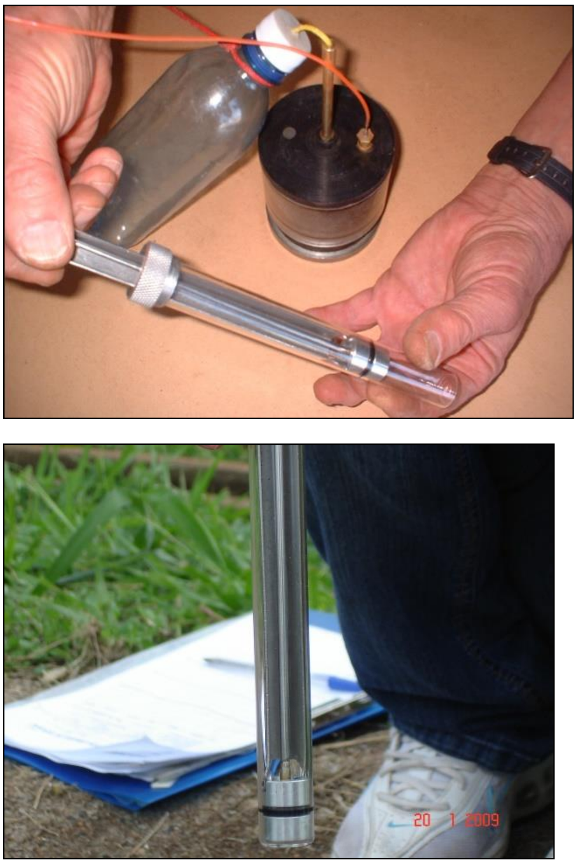

Figura 9. Ampola de vidro com pistão ligado ao canalículo de transferência dos gases coletados.

Essas coletas são realizadas para determinar os gases presentes no interior da câmara, que representam os gases e a dinâmica dos mesmos na interface água-ar. As concentrações dos gases são obtidas por análise cromatográfica utilizando detectores de condutividade térmica e ionização de chama, o que permite calcular as taxas de emissão pelo método de difusão. Estas são expressas em mg C m^{-2} d^{-1}.

ANÁLISE CROMATOGRÁFICA

1. O cromatógrafo precisa ser previamente calibrado com uma mistura gasosa padrão, fabricado pela Air Liquide, contendo 11 ppm de metano (CH_4) e 768 ppm de gás carbônico (CO_2). O padrão utilizado para nitrogênio (N_2) é o próprio ar ambiente, com 78% N_2;

2. Antes de iniciar a operação, lave os dutos de transferência com a própria amostra;

3. Retire 3 mL de amostra da ampola gasométrica;

4. Injete o gás na coluna cromatográfica de aço inox empacotada com polímero de divinilbenzeno “HayeSep D”, coluna esta seguida por detector de condutividade térmica, para análise cromatográfica do gás carbônico presente na amostra;

5. Obtido o resultado da concentração de gás carbônico, retira-se 1 mL de amostra da mesma ampola, para injeção em outra coluna cromatográfica, também "HayeSep D", coluna esta seguida por detector de ionização de chama, para análise cromatográfica do gás metano presente na amostra;

6. Obtido o resultado da concentração de gás metano, retira-se 300 µL (microlitros) da amostra da mesma ampola para injeção em uma terceira coluna cromatográfica de aço inox, empacotada com Peneira Molecular 5Å, coluna esta seguida por detector de condutividade térmica, para análise cromatográfica do gás nitrogênio presente na amostra.

Exemplos de cálculos dos fluxos de gases do efeito estufa a partir dos resultados das análises cromatográficas

Injetar 3 mL da mistura padrão da Air Liquide contendo 768 ppm de CO_2 no cromatógrafo produzindo um pico de CO_2 no cromatograma, pico este com 30060 unidades de área (ua)*. Outra injeção resultou em 31611 ua. O fator de calibração (Fc) é dado por:

$$M = \frac{30060 + 31611}{2} = 30835.5$$

M = Média das áreas dos picos do cromatograma

$$Fc = \frac{768}{M} = 0{,}024906 \text{ ppm } CO_2 \text{ ua}^{-1}$$

A injeção de 1 mL da amostra "0 min" do viveiro de aquicultura resultou em um pico de CO_2 com área 21882 e, portanto, com concentração:

- 21882 x 0,024906 = 545 ppm CO_2.

Em seguida, injeção de 1 mL da amostra "1 min" do viveiro de aquicultura resultou em um pico de CO_2 com área 24773 e, portanto, com concentração:

- 24773 x 0,024906 = 617 ppm CO_2.

Em seguida, injeção de 1 mL da amostra "2 min" do viveiro de aquicultura resultou em um pico de CO_2 com área 24572 e, portanto, com concentração:

- 24572 x 0,024906 = 612 ppm CO_2.

Por fim, injeção de 1 mL da amostra "4 min" do viveiro de aquicultura resultou em um pico de CO_2 com área 30595 e, portanto, com concentração:

- 30595 x 0,024906 = 762 ppm CO_2.

* Unidade de área corresponde ao preenchimento (pixels) da área correspondente a um pico de concentração do gás inserido no cromatógrafo.

O cálculo detalhado da emissão de CO_2, CH_4 e N_2 do viveiro de aquicultura, segue abaixo.

Exemplo de cálculo da emissão de CO_2

Elaboração do gráfico (x-t) das concentrações de CO_2 obtidas nos tempos (T1, T2, T3 e T4) do viveiro de aquicultura (545; 617; 612; 762 ppm CO_2) (Figura 10).

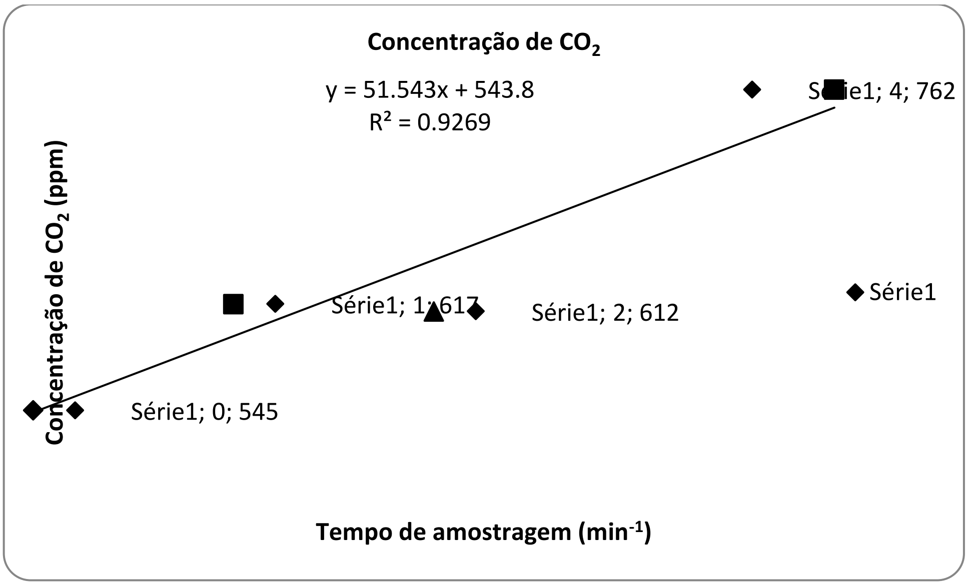

Figura 10. Resultado da serie temporal de concentração de CO_2 no viveiro de aquicultura. *O coeficiente angular (51,5 ppm CO_2 min^{-1}) quantifica a taxa de emissão de CO_2 da interface água-ar para a câmara.*

$$y_{(ppm\ CO2)} = 51,543\ t_{(min)} + 543,8$$

Para o cálculo da emissão, é necessário primeiro saber quantos moles de CO_2 há em 1 ppm do volume da câmara (1 L). Estes moles estão nas condições (687 mmHg e 290,2 K) do laboratório onde foi feita a análise:

$$P \,.\, V = nRT$$

$$n = \frac{687[mm\,Hg] \times (\frac{1}{10^6})[L\;ppm^{-1}]}{62{,}4[\frac{mm\,Hg\,L}{moles\,K}] \times 290{,}2[K]} = 3{,}79 \times 10^{-8}\,\frac{moles}{ppm}$$

P = 687 mmHg;
V = $1/10^{-6}$ = volume de 1L;
R = 62,4 mmHg L;
T = temperatura em Kelvin

O número de moles de CO_2 emitidos pelo viveiro de aquicultira, ao longo do tempo amostrado:

$$51{,}5\,\frac{ppm\,CO_2}{\min} \times 3{,}79 \times 10^{-8}\,\frac{moles}{ppm} = 1{,}951 \times 10^{-6}\,\frac{moles\,CO_2}{\min}$$

Assim, a emissão de CO_2 expressa em miligramas de CO_2 por dia por metro quadrado de área amostrada do viveiro de aquicultura (área da câmara é 0,049 m^2) é:

$$1{,}951 \times 10^{-6}\,\frac{moles\,CO_2}{\min} \times \frac{44g}{mole} \times \frac{1000\,mg}{g} \times \frac{60\min}{h} \times \frac{24h}{d} \times \frac{1}{0{,}049\,m^2} = 2523\,\frac{mg\;CO_2}{m^2\;d}$$

Exemplo de cálculo da emissão de CH_4

Elaboração do gráfico (x-t) dos quatro resultados tomados como serie temporal (T1, T2, T3 e T4) de concentração de CH_4 do viveiro de aquicultura (2,31; 2,19; 2,50 ; 2,52 ppm CH_4) (Figura 11).

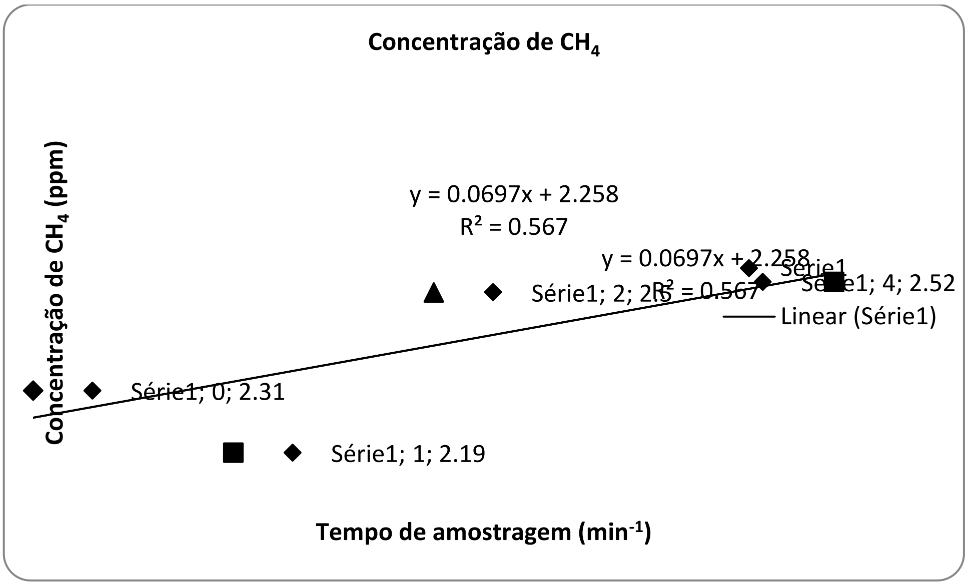

Figura 11. Resultado da serie temporal de concentração de CH_4 do viveiro de aquicultura. *O coeficiente angular (0,0697 ppm CH_4 min^{-1}) quantifica a taxa de emissão de CH_4 da interface água-ar para a câmara.*

$$y_{(ppm\ CH4)} = 0{,}0697\ t_{(min)} + 2{,}258$$

Para o calculo da emissão, é necessário primeiro saber quantos moles de CH_4 há em 1 ppm do volume da câmara (1 L), moles estes nas condições (687 mmHg e 290,2 K) do laboratório onde foi feita a analise:

$$P\ .V = nRT$$

$$n = \frac{687[mm\,Hg]\times(\frac{1}{10^{6}})[L\ ppm^{-1}]}{62{,}4[\frac{mm\,Hg\,L}{moles\,K}]\times 290{,}2[K]} = 3{,}79\times10^{-8}\,\frac{moles}{ppm}$$

O numero de moles de CH_4 emitidos pelo viveiro de aquicultura, ao longo do tempo amostrado:

$$0{,}07\,\frac{ppmCH_4}{\min}\times 3{,}79\times10^{-8}\,\frac{moles}{ppm} = 2{,}653\times10^{-9}\,\frac{molesCH_4}{\min}$$

Assim, a emissão de CH_4 expressa em miligramas de CH_4 por dia por metro quadrado de área do viveiro de aquicultura amostrada (área da câmara é 0,049 m^2) é:

$$2{,}653\times10^{-9}\,\frac{moles CH_4}{\min}\times\frac{16g}{mole}\times\frac{1000mg}{g}\times\frac{60\min}{h}\times\frac{24h}{d}\times\frac{1}{0{,}049m^2}=1{,}25\,\frac{mg\;CH_4}{m^2\,d}$$

Exemplo de cálculo de emissão de N_2

Elaboração do gráfico (x-t) dos quatro resultados tomados como serie temporal (T1, T2, T3 e T4) de concentração de N_2 viveiro de aquicultura (77; 78; 78; 78 % N_2), (Figura 12).

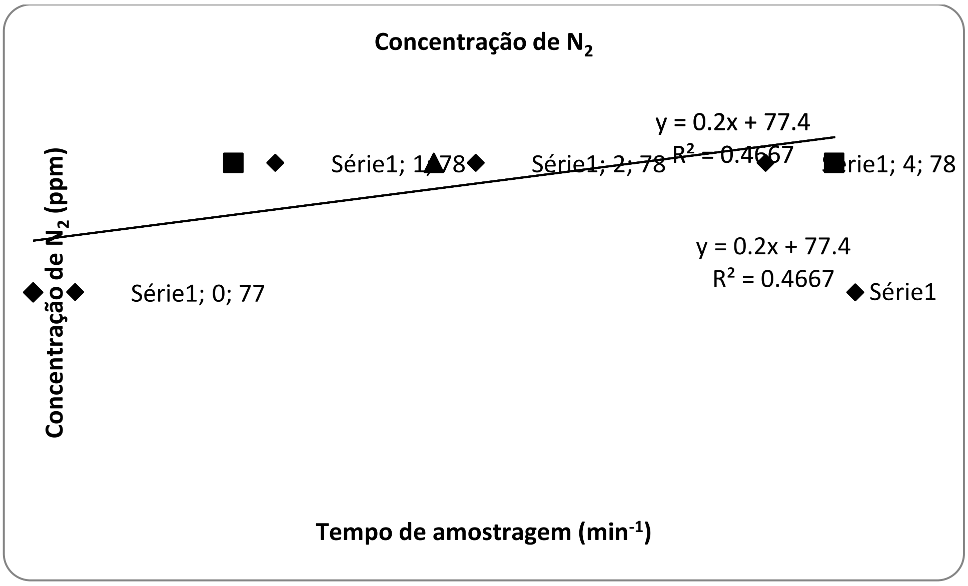

Figura 12. Resultado da serie temporal de concentração de N_2 no viveiro de aquicultura. O coeficiente angular (0,2 % N_2 min^{-1}) quantifica a taxa de emissão de N_2 da interface água-ar para a câmara.

$$y_{(\%\,N2)} = 0{,}2\,t_{(min)} + 77{,}4$$

Para o calculo da emissão, é necessário primeiro saber quantos moles de N_2 há em 1 % do volume da câmara (1 L), moles estes nas condições (687 mmHg e 290,2 K) do laboratório onde foi feita a analise:

$$\mathbf{P.\,V = nRT}$$

$$n=\frac{687[mm\,Hg]\times(\frac{1}{10^2})[\frac{L}{\%}]}{62{,}4[\frac{mm\,Hg\,L}{moles\,K}]\times290{,}2[K]}=3{,}7938\times10^{-4}\,\frac{moles}{\%}$$

O número de moles de N_2 emitidos pelo viveiro de aquicultura, ao longo do tempo amostrado:

$$0{,}2\frac{\%\,N_2}{\min}\times 3{,}79\times 10^{-4}\,\frac{moles}{\%}=7{,}58\times 10^{-5}\,\frac{moles\,N_2}{\min}$$

Assim, a emissão de N_2 expressa em miligramas de N_2 por dia por metro quadrado de área amostrada do viveiro de aquicultura (área da câmara é 0,049 m^2) é:

$$7{,}58\times 10^{-5}\,\frac{moles\,N_2}{\min}\times\frac{28g}{mole}\times\frac{60\min}{h}\times\frac{24h}{d}\times\frac{1}{0{,}049m^2}=62\,\frac{g\ N_2}{m^2\,d}$$

CONSIDERAÇÕES FINAIS

A adoção de estratégias eficazes que promovam a redução das emissões de gases do efeito estufa só serão possíveis com estudos que considerem aspectos individuais de produção da atividade, quantificando a emissão dos gases levando em consideração as estratégias de cultivos, os sistemas de manejo e as características locais de solo e clima. A questão das mudanças climáticas precisa, portanto, passar por uma avaliação mais detalhada com o intuito de se determinar o papel da natureza e da ação humana nesse processo, mesmo porque as duas esferas podem atuar de forma solidária e intercambiando influências. Por isso, torna-se necessário uma concentração de esforços para entender o sistema aquícola sob uma ótica macroscópica, bem como também compreender a interação entre suas dimensões, permitindo um entendimento global da atividade, como também a formação de conhecimento crítico para a sustentabilidade do sistema em estudo. Assim, a análise dos gases do efeito estufa na aquicultura parece ser uma alternativa a seguir para um entendimento mais profundo entre a relação da atividade com o meio ambiente.

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