Sustainability of Farming Nile Tilapia in Net-Cages in a Reservoir of the Brazilian Semi-Arid Region During an Extended Drought Event

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Abstract

Stakeholders in the aquaculture industry are currently seeking the development of sustainable production systems and methodologies to measure sustainability. The present study evaluated the environmental, social and economic dimensions of sustainability of a net-cage tilapia production system with two stocking densities implemented in a reservoir in the semi-arid northeast region of Brazil during an extended drought event. The three dimensions of sustainability were evaluated through a set of 33 indicators. The Internal Rates of Return were below the Minimum Attractive Rates of Return and the Net Present Value indicator was negative for both stocking densities, showing no attractive financial benefits and no capital return 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/m³, respectively. Various age groups and ethnic groups were represented among the employees, but the enterprise was operated only by men. Phosphorus accumulations were 2.1 and 2.0 kg/tonne and particulate material accumulations of 110 and 100 kg/tonne for 125 fish/m³ and 100 fish/m³, respectively. The prolonged drought conditions that occur in the Brazilian semiarid region can compromise the environmental, economic and social sustainability of fish farming in reservoirs in the region.

Introduction

The global aquaculture industry was estimated to consist of 19 million participants, most of which are in Asia, the Caribbean, and Central and South American countries (FAO 2020). When considering the objectives described in the 2030 Agenda for Sustainable Development (UN 2019), modern aquaculture must contribute to food security, sustainable use of water, reducing the discharge of effluents and chemicals, promoting inclusive economic growth and establishing other sustainable production standards. The increase in aquaculture production worldwide is due to the rising demand for healthy and nutritionally adequate foods (Boyd et al. 2020; Zhong et al. 2021). Therefore, the sector must adapt to an ever-increasing global fish consumption by generating alternative products and higher yields while improving management of wastes, production techniques, and the efficiency of using natural resources, without negatively affecting the safety of the food products (Rodrigues et al. 2019; Dantas et al. 2020; De Vasconcelos et al. 2021; Guzmán-Luna et al. 2021).

In Brazil, aquaculture is estimated to increase by 32% by 2030, with a production of 800 thousand tonnes (FAO 2020). Funding for advancements in Brazilian aquaculture have been due to large investments in the sector over recent years and the creation of public policies that promote participation in the activity (Garcia et al. 2014; Bueno et al. 2015; Padial et al. 2017). The Nile tilapia (*Oreochromis niloticus*) is currently the main species used for fish farming in Brazil and its production in 2019 was 432,000 t, which was 57% of national production. Tilapia farming in Brazil is mostly carried out in net-cage systems installed in public reservoirs (Demétrio 2012; Araújo et al. 2017; Lima et al. 2018; Chaves et al. 2020; Moraes et al. 2020). The use of net-cage systems in reservoirs has allowed the rapid expansion of inland

fish farming since no investment is required for obtaining land and constructing ponds (Nunes and Rocha 2015).

The implementation of Nile tilapia net-cage culture in reservoirs of the semi-arid Brazilian northeast led to the creation of employment opportunities and improvements in the quality of life of several families (Lopes et al. 2017). However, this region is subject to prolonged drought conditions that can compromise the use of reservoirs for fish farming (Costa et al. 2019; Henry-Silva et al. 2019; Leite and Becker 2019). In addition, the intensive level of this farming activity may have low environmental sustainability in this region given the potential impacts of eutrophication from the high feed requirements (Venturoti et al. 2015; Degefu et al. 2019), greenhouse gas emissions from the accumulation of nutrients, and the risk of introducing an exotic species in the natural environment (Gorlach-Lira et al. 2013; Lima Junior et al. 2018; Yuan et al. 2017; Cacho et al. 2020). Pollution from this system may also limit other uses of the reservoir such as water supply and fishing when considering reduced water levels in a region with prolonged droughts (Sharmin et al. 2019).

Aquaculture production systems should be assessed and compared to each other based on their economic, environmental, and social aspects of sustainability (Moura et al. 2016; Milewski and Smith 2019; Nobile et al. 2019). Analyses regarding the sustainability of aquaculture activities include the emergy synthesis (Garcia et al. 2014; David et al., 2018; David et al. 2020; Maiolo et al. 2021), ecological footprint (Galli et al. 2016; Chang et al. 2017), life cycle analysis (Pahri et al. 2015; Maiolo et al. 2020), 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; Valenti et al. 2018). Sets of indicators can be understood as a measure of a production system component, which can provide empirical data for comparison and clarity regarding a certain phenomenon (Heink and Kowarik 2010). Indicators allow for comparisons across various aquaculture systems as carried out in different regions of the world and on different time scales (Valenti et al. 2018). In Brazil, the Aquaculture Sustainability Research Network consists of scientists from research institutions in all regions of the country and has been developing and improving sustainability indicators to assess the sustainability of various Brazilian aquaculture systems (Moura et al. 2016; Valenti et al. 2018, Pereira et al. 2021). This research aims to subsidize public policies, encourage the development of sustainable aquaculture activities and assist in the creation of a startup for farm certification (Valenti et al., 2021). Given the importance of understanding the sustainability of fish production in cages and the development of effective analytical methods, the present study described the environmental, social and economic dimensions of sustainability of a net-cage tilapia production system implemented by a commercial cooperative in a reservoir in the semi-arid northeast region of Brazil during an extended drought event.

Materials And Methods

The present study was carried out by accompanying a Nile tilapia farming cooperative in the Umari reservoir, located in the Brazilian semi-arid northeast region (5 °42'13"S and 37 °15'18"W) (Fig. 1). The fish were reared in net-cages and managed by 13 entrepreneurs that formed the cooperative, which had a

workforce of 15 employees. This production model implemented in Umari is the most used in Brazil, including the creation of large aquaculture parks in public and hydroelectric reservoirs. This fish farming cooperative showed an annual production of ~281 tonnes of Nile tilapia. The production is sold as whole fish (98%) and eviscerated fish (2%). 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 hot and semi-arid climate and with the rainy season occurring in late autumn. Between 2012 and 2017 there was a gradual reduction in the volume of the reservoir, due to the suprasonal drought that affected most of the Brazilian semiarid region (Henry-Silva et al. 2019). During the observation period, the percentage of reservoir volume in relation to its maximum volume ranged from 19–21% (Fig. 2).

The cooperative of the Umari reservoir was observed each month from October 2015 to January 2016 during a tilapia production cycle, from stocking to harvest. Tilapia were obtained with an average individual biomass of 5.3 grams and were reared in an intermediate grow-out phase for two months in the Umari reservoir. Tilapia juveniles (118.5 ± 5 g) were obtained after rearing in the intermediate grow-out phase and were restocked in 6 m³ net-cages (2×2×1.5 m) for another two months at 100 and 125 fish/m³ (600 and 750 fish per cage, respectively) for a production cycle of four months (two months of intermediate grow-out and two months of final grow-out, which occurred simultaneously at the cooperative). The structure of the net-cages consisted of steel rods to support a galvanized wire mesh enclosure and closed drums were used to maintain the cages floating. The net-cages were set at approximately eight meters from the reservoir bottom.

Fish from four net-cages of each density were randomly selected and analyzed. A sample of 5% of fish in each of the selected net-cages were weighed weekly and the mean weight calculated to estimate the biomass in each cage and the mean individual weight of the fish. The biomass values were calculated by multiplying the mean individual weight by the estimated total number of fish in each cage, which was based on the difference between the initial fish population and the daily monitoring of fish mortality. Fish were counted and weighed at the harvest to determine the final average mass, survival, and apparent feed conversion ratio. The fish were fed with a pelleted commercial feed (40% crude protein) until the first thirty days of cultivation and, subsequently, extruded feed was provided with 32% crude protein. The feed was offered twice daily according to the total biomass of the stocked fish, which was estimated weekly to adjust the feed quantity. The initial feeding rate was 4.5% of the stocked biomass. This amount decreased weekly until reaching 3.1% of the stocked biomass at the end of the experiment. The environmental, social and economic sustainability were evaluated based on three production cycles per year.

A set of seven indicators was used to evaluate the economic sustainability. The indicators represented 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 during the production were surveyed. Cost-return and cash flow analyses were performed (Engle 2010). The initial investment

included net-cages, canoe, electronic balance to weigh biomass, management platform, sheds and other items of low cost. 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.

A set of seven indicators was used to evaluate environmental sustainability (Table 2). These indicators 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 were quantified each month by placing sedimentation chambers (in duplicate) on the reservoir bottom and under each net-cage 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 concentration of total phosphorus (Koroleff 1983) of the sedimentation was calculated by subtracting the natural sedimentation concentration (control) of this nutrient from the sedimentation concentration recorded below the net-cages.

Social sustainability was evaluated using a set of 17 indicators (Table 1). These indicators represent four major 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 through 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 of the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística – IBGE) and the Ministry of Fisheries and Aquaculture (Ministério da Pesca e Aquicultura – MPA).

Table 1

Indicators of economic, environmental and social sustainability. Space and resources to produce the feed were excluded from analyses of these indicators.

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	General Chemical Pollution	Proportional Cost of Work
3	Benefit-Cost Ratio	Pollution by Hormones	Remuneration of Work per Unit of Production
4	Net Present Value	Accumulation of Phosphorus	Racial Inclusion
5	Net Profit	Accumulation of Organic Material	Gender Inclusion
6	Risk Rate	Accumulation of Particulate Material	Age Inclusion
7	Diversity of Products	Risk of Farmed Species	Required Work per Unit of Occupied Area
8	Diversity of Markets		Required Work per Unity of Production
9	Invested Capital Generated in the Activity		Proportion of Self-Employments
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

Survival was 90% and the Apparent Feed Conversion Ratio was 1.5 for both stocking densities. Mean final weight was 316.9 grams and 358.8 grams for the stocking densities of 125 and 100 fish/m³, respectively. Fish farmers anticipated harvesting by a few months due to the reduction in the volume of the Umari reservoir. This early harvest reflected negatively on economic indicators. All investments to implement the net-cage production system were 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 made of wood, shed for production and employee support, electronic balance for weighing biomass and other items of low cost, totaling US\$ 93,445. No reinvestments were made for new net-cages since the environmental licenses permitted a maximum of 37 cages per producer. 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 tilapia production. The economic sustainability indicators showed that the production system carried out with a stocking density of 125 fish/m³ 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 that the system was economically unfeasible. The production system with 100 fish/m³ generated an Internal Rate of Return (5%) and a negative Net Present Value (US\$ -47821.30), indicating that this system was not economically feasible as well (Table 2). The relationship between average annual income and investment was relatively low (<US\$ 1.00) for both stocking densities. The producers used the profit to compensate for fish mortality, administration of the production, control of inputs and sales.

The economic indicator Risk Ratio consisted of 11 factors that increase the risks of negative impacts on aquaculture. In the present study, this indicator was of 18% for both stocking densities. Only two of the 11 factors 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, which were whole fish (~98% of total production) and fillets (~2%). The cooperative focused on the 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 Nile tilapia farming in net-cages in the Umari reservoir as carried out by a commercial cooperative and with densities of 125 and 100 fish/m³.

Economic Indicators	125 fish/m³	100 fish/m³
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/m³, respectively. The pay equity was 80% for both tilapia densities. 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 the two densities. 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/m³, respectively, whereas the other acquisitions were made in other municipalities or states. Local consumption showed that only 10% of the fish was commercialized and consumed in the municipality through small merchants.

Employees of the cooperative received health benefits through a public federal health system known as the Unified Health System, which is available in most Brazilian municipalities. The management model for this system is decentralized, with the federal government, states and municipalities working together to ensure free health care for all citizens. This health service is maintained by tax revenues from private health programs. 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 in community activities, 100% of employees showed association 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 Nile tilapia farming in net-cages in the Umari reservoir as carried out by a commercial cooperative and with densities of 125 and 100 fish/m³

Indicators of Social Sustainability	125 fish/m ³	100 fish/m ³
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. Ethnic groups Inclusion (%)	75	75
5. Gender Inclusion (%)	52	52
6. Age Inclusion (%)	41	41
7. Required Work per Unit of Occupied Area (MHY/m ²)	2	2
8. Required Work per Unity of Production (MH/kg)	0.13	0.15
9. Proportion of Self-Employments (%)	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 (%)	100	100
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. The 125 fish/m³ 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 100 fish/m³ 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 produced for the stocking densities of 125 and 100 fish/m³, respectively. Pollution from herbicides, pesticides and hormones was zero since none of these products were used in the net-cage system in the present study. The production system generated 106 kg and 101 kg of particulate material per tonne of fish produced for the densities of 125 and 100

fish/m³, respectively. Approximately 90% of this emission consisted of organic matter for both densities (Table 4).

Table 4
Values obtained for the indicators of environmental sustainability for Nile tilapia farming in net-cages in the Umari reservoir as carried out by a commercial cooperative and with densities of 125 and 100 fish/m³

Indicators of Environmental Sustainability	125 fish/m ³	100 fish/m ³
1. Use of Space (m ² /kg)	0.27	0.29
2. General Chemical Pollution (kg fish/tonne)	0	0
3. Pollution by Hormones (kg fish/tonne)	0	0
4. Accumulation of Phosphorus (kg fish/tonne)	2.1	2.0
5. Accumulation of Organic Material (kg fish/tonne)	99	89
6. Accumulation of Particulate Material (kg fish/tonne)	106	101
7. Risk of Farmed Species	5	5

Discussion

Both stocking densities of the Nile tilapia in the net-cage production system of the cooperative of the Umari reservoir showed no economic feasibility according to the indicators. The internal rates of return (5 to 7%), benefit-cost ratios (US\$ 0.44 to US\$ 0.69), and net present values (US\$ -26619.70 to US\$ -47821.30) for both tilapia densities in 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 as managed by an association. The net-cage system in Moura et al. (2016) showed an internal rate of return of 52% per year, a benefit-cost ration of US\$ 1.35, and a positive net present value of US\$ 47773.09. It is noteworthy that a cooperative farming system differs from an association regarding certain aspects of the cash flow. The association in Moura et al. (2016) paid no taxes on the revenue nor the financial obligations and salaries of the employees since they had more autonomy in their productions. In addition, the final stocking density of tilapia in Moura et al. (2016) was 200 fish/m³ and the marketed size was at 400 grams per individual fish sold at US\$ 2.51 to US\$ 3.51/kg.

Average profitability values in the present study were lower than those obtained by an association of fish farmers in the Brazilian northeast semi-arid region, which showed annual profitability of 23% for the net-cage production of Nile tilapia (200 fish/m³) and was exempt from taxes while receiving economic subsidies (Moura et al. 2016). Nearly all (98%) of the 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, resulting 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 effectively transformed into income. This was 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. Of the 11 items used to determine this indicator, only the absence of a business plan during the planning phase for implementation and institutional instability were observed, since instability may occur due to changes in environmental laws. However, this indicator also 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 fish diseases 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.

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

The number of individuals that received benefits was low despite the activity providing direct and indirect employment opportunities for approximately 130 intermediaries and small merchants. However, the generation and distribution of income have more social relevance when considering the possibility that each worker represented a family. 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 low education. Only one of the 15 employees studied while the others had incomplete elementary or high school education. Various age groups and ethnic groups 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.

Approximately 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. 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. Although the employees of the cooperative had no access to private health programs, they all had access to the public federal health system. 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 observed in the present study was due to the purchases of major inputs (including feed and fingerlings) from other municipalities and states, minimizing local purchases for basic maintenance items from local retail, as well as occasional lodging for members, fuel, ice and other items of low impact on the local economy. This is especially relevant since feed and fingerlings usually show the highest proportions of total operating costs in fish farming activities (Barbosa et al. 2020). However, local retention of income becomes 90% on the state level, showing that minimal financial resources are destined to other states. The retention of resources invested in the activity, especially feed and fingerlings, can become higher if these items were produced in the city of Upanema - RN, where the Umari reservoir is located. 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 local social and economic development.

The value of pollution by herbicides, pesticides and hormones in the present study was considered zero since none of these products were used, giving a positive externality of the productions in an environmental point of view. On the other hand, the production systems showed reduced environmental sustainability due to the accumulation of phosphorus at 2.1 and 2.0 kg/tonne, particulate material at 110 and 100 kg/tonne, and organic material at 99 and 89 kg/tonne for the densities of 125 and 100 fish/m³, respectively. Moura et al. (2016) reported that phosphorus accumulated in the sediment at 0.9 kg of phosphorus per tonne of fish produced for net-cage tilapia farming in a reservoir of the same region as the present study. The high release of phosphorus is among the most detrimental impacts from fish farming since it promotes eutrophication in aquatic environments, eventually 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 total phosphorus concentrations in the sediment below the net-cages and adjacent areas. Changes in the bottom sediments from the accumulation of suspended solids were also observed in the area that surrounds the fish farming systems analyzed in southeast Asia (Huang et al. 2012; Guo and Li 2003). 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, which reduces

dissolved oxygen through microbial aerobic decomposition (Flickinger et al. 2020a). In general, the present study showed that environmental sustainability was 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. Consideration must also be given to investments for the construction of artificial ponds to optimize water use, which may provide longer continuity for this activity when compared to the use of reservoirs in the Brazilian semi-arid region. Earthen ponds facilitate the control of wastes and the escape of exotics when compared to reservoirs. Recent studies have shown the technical feasibility of integrating prawns in earthen ponds with fish as free-swimming or in net-cages, and that these IMTA systems may prolong the use of water given the improved conversion of nutrient inputs into harvested biomass (Flickinger et al. 2019; Rodrigues et al. 2019; Dantas et al. 2020; Flickinger et al. 2020a; Flickinger et al. 2020b).

It is important to note that the semi-arid northeast region of Brazil has experienced a prolonged drought between 2012 and 2017, with several locations within the region showing rainfall below historical averages (Costa et al. 2019; Henry-Silva et al. 2019; Leite and Becker 2019). 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, approximately 70% of the reservoirs in the state that have a water capacity above 5,000,000 m³ were practically dry (<1% of total volume). In 2016, when the Umari reservoir was 18% of its total volume, the possible turbulent vertical circulation favored the mixing of the entire water column and as a consequence, the reduction of dissolved oxygen and a mortality about 60 tonnes of Nile tilapia (Henry-Silva et al. 2019). As a result, fish farming in net-cages in the Umari reservoir was temporarily suspended and resumed recently on a much smaller scale, with only four producers investing in the activity and producing about 80 tonnes of Nile tilapia annually. In March 2020, the reservoir remained with a reduced volume, with only 32% of its total volume (SEMARH 2020).

The fish farming in net-cages must consider the hydrological characteristics of the reservoirs since variations in their water level can drastically reduce the sustainability of this activity. 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), of which a reduced water level combined with turbulent vertical circulation may result in mortality of fish reared in net-cages (Henry-Silva et al. 2019). Thus, the sustainability of net-cage fish farming in the Umari reservoir and other reservoirs in the Brazilian semi-arid region are also related to the volume of these aquatic environments and the length of drought periods.

Declarations

Ethical Approval: This is a research article following the ethical standard of the institution.

Consent to Participate: Not applicable

Consent to Publish: Not applicable

Author Contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Gustavo Gonzaga Henry-Silva and Júlio César da Silva Cacho. The first draft of the manuscript was written by Gustavo Gonzaga Henry-Silva and Júlio César da Silva Cacho and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

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.

Figure 2

Mean, minimum and maximum values of volumes (% in relation to the total) of the Umari reservoir between the years 2002 and 2020. *Reservoir filling started in 2002. ** Water depth above the maximum level. Arrows: years of monitoring of Nile tilapia cultivation in the reservoir (2015/2016).