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Scientific Article

Carrying capacity for Nile tilapia production in net cages in tropical reservoirs during an extreme drought

Rodrigo Sávio Teixeira de Moura[1], Ronaldo Angelini[2], Nara Poliana Meneses de Oliveira[3], Wagner Cotroni Valenti[4], Gustavo Gonzaga Henry-Silva[3]*

[1]Universidade Federal do Maranhão – Human, Natural, Health and Technology Science Center - Pinheiro (MA), Brazil.
[2]Universidade Federal do Rio Grande do Norte – Department of Civil and Environmental Engineering - Natal (RN), Brazil.
[3]Universidade Federal Rural do Semi-Árido – Department of Biosciences - Mossoró (RN), Brazil.
[4]Universidade Estadual Paulista "Júlio de Mesquita Filho" – Aquaculture Center - Jaboticabal (SP), Brazil.
*Corresponding author: gustavo@ufersa.edu.br

ABSTRACT

This study assessed the production carrying capacity for Nile tilapia (Oreochromis niloticus) in net cages in reservoirs of the Brazilian semi-arid region during a supra-seasonal drought. It used the phosphorus mass balance models to estimate nutrient assimilation, with phosphorus concentration limits in the water column were set at 30 μg·L^{-1}, according to Brazilian legislation, and 60 μg·L^{-1} for eutrophied environments. In the Santa Cruz reservoir, the phosphorus assimilation capacity was 5,848 kg·year^{-1} at 60 μg·L^{-1}, while in Umari it was 572.7 kg·year^{-1} at 30 μg·L^{-1} and 4,620 kg·year^{-1} at 60 μg·L^{-1}. The carrying capacities were 680 tonnes in Santa Cruz at 60 μg·L^{-1}, and in Umari, 63 tonnes at 30 μg·L^{-1} and 508 tonnes at 60 μg·L^{-1}. Despite higher phosphorus loading in Umari, Santa Cruz showed greater capacity at 60 μg·L^{-1} due to its larger water volume. The study highlights the importance of reservoir morphometry and hydrological parameters for aquaculture sustainability during extreme droughts, and uses mass balance models to propose practices that balance production and environmental conservation.

Keywords: Mass balance; Fish farming; Phosphorus; Water quality.

Capacidade de suporte para produção de tilápia-do-Nilo em tanques-rede em reservatórios tropicais durante uma seca extrema

RESUMO

Este estudo avaliou a capacidade de suporte para produção de tilápia-do-Nilo (Oreochromis niloticus) em tanques-rede em reservatórios do semiárido brasileiro durante uma seca suprassazonal. O mesmo Utilizou modelos de balanço de massa de fósforo para estimar a assimilação de nutrientes, com limites de concentração de fósforo na coluna d'água foram estabelecidos em 30 μg·L^{-1}, segundo a legislação brasileira, e 60 μg·L^{-1} para ambientes eutrofizados. No reservatório de Santa Cruz, a capacidade de assimilação foi de 5.848 kg·ano^{-1} a 60 μg·L^{-1}, enquanto em Umari foi de 572,7 kg·ano^{-1} a 30 μg·L^{-1} e 4.620 kg·ano^{-1} a 60 μg·L^{-1}. As capacidades de suporte para produção foram 680 toneladas em Santa Cruz a 60 μg·L^{-1} e em Umari, 63 toneladas a 30 μg·L^{-1} e 508 toneladas a 60 μg·L^{-1}. Apesar das maiores emissões de fósforo em Umari, Santa Cruz apresentou maior capacidade a 60 μg·L^{-1} devido ao maior volume de água. O estudo ressalta a importância da morfometria e dos parâmetros hidrológicos para a aquicultura em secas extremas, propondo, por meio de modelos de balanço de massa, práticas que equilibram produção e conservação ambiental.

Palavras-chave: Balanço de massa; Piscicultura; Fósforo; Qualidade da água.

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INTRODUCTION

Reservoirs play essential roles in regional socio-economic development, and among its many uses, fish farming in net cages is one of the fastest growing, mainly to sustain the increasing demand for fish (Bueno et al., 2015; Noori et al., 2024; Starling et al., 2024; Valenti et al., 2021). Fish farming contributes to generating jobs and income for the population, increasing food security for the riverside population (Béné et al., 2016; Bjørndal et al., 2024; Lopes et al., 2017). However, fish farming may be also an anthropogenic pressure that can accelerate the eutrophication process (Moura et al., 2016), interfering with the structure and functioning of aquatic ecosystems (Bartozek et al., 2014; Kang et al., 2022; Latini et al., 2021; Moura et al., 2023; Naderian et al., 2024; Ramos et al., 2013).

The main impacts of fish farming in net cages derive from uneaten feed, feces, and excreta of the farmed animals, resulting in solid and dissolved residues release (Arruda et al., 2017; Roriz et al., 2017). The decrease in water quality is related to organic matter residues from the diets used in fish farming systems, which are one of the main factors for the increase of phosphorus and nitrogen in the reservoirs (Fialho et al., 2021). The reduced digestibility of food can also alter the water quality of reservoirs in which fish are farmed in cages (Bueno et al., 2023). The impacts of these effluents are concentrated in the areas around the net cages, modifying the characteristics of the water and sediments, but they can be extended in hundreds of meters away from where fish farming activities are carried out (Cacho et al., 2020; Wang et al., 2024).

The vulnerability of reservoirs increases with extreme climate events. These events are predicted to be more frequent with climate changes (Costa et al., 2019; Noori, Bateni et al., 2022; Noori, Woolway et al., 2022; Seigerman et al., 2024). Nutrient wastes from fish farming and long droughts can worsen water quality and restrict the multiple uses of the reservoirs (Jeppesen et al., 2015; Rigosi et al., 2014; Umaña, 2014). This scenario is especially critical, as the Brazilian semi-arid region was recently subjected to the most severe drought in the last 60 years (Cunha et al., 2019; Marengo et al., 2018). The impacts of global warming on reservoirs in semi-arid regions alter nutrient concentrations in water column, aquatic metabolism, community structure, and the functioning of aquatic ecosystems, which can gradually become more eutrophic, compromising their ability to regulate water quality and provide fisheries resources (Henry-Silva et al., 2022; Kim et al., 2024; Rocha Junior et al., 2018; Santos et al., 2021).

In this context, empirical mass balance models, such as the one proposed by Dillon and Rigler (1974), are useful for predicting production scenarios in reservoirs, especially about fish cultivation in net cages and their possible impacts on the increased phosphorus input, avoiding compromising its multiple uses (Canzi et al., 2017; David et al., 2015; Hamid et al., 2022; Weitzman & Filgueira, 2019).

Ecological carrying capacity is the level of aquaculture production that the ecosystem can support without causing undesirable changes in ecological processes, species composition, and aquatic populations and communities (Filgueira et al., 2015; McKindsey et al., 2006; Weitzman et al., 2021). Phosphorus is the most used nutrient in determining the carrying capacity of freshwater environments for fish farming, because it is considered the primary element that triggers eutrophication (Montanhini Neto & Ostrensky, 2015; Naderian et al., 2024). The most common forms of phosphorus effluent from net cages are:

- Dissolved organic phosphorus from the excreta of cultivated animals, rapidly absorbed by primary producers, which can cause algae blooms and deteriorate water quality (Canale et al., 2016);
- Particulate organic phosphorus, from uneaten feed and feces of farm animals, which accumulates in the sediment, affecting its composition and altering the benthic community (Srithongouthai & Tada, 2017).

In this context, the present study aimed to evaluate the carrying capacity for Nile tilapia (*Oreochromis niloticus*) production in net cages in two reservoirs of the Brazilian semi-arid, during an extreme hydrological event of supra-seasonal drought.

MATERIALS AND METHODS

Study area

The study was conducted in the reservoirs Santa Cruz and Umari, located in the Apodi/Mossoró River watershed, in Rio Grande do Norte state, Brazil (Fig. 1). These reservoirs have the potential for irrigation, water harvesting, fishing, and fish farming in net cages. The Santa Cruz reservoir can accumulate 600 million m^3 of water and has a watershed of 4,264 km^2. In comparison, Umari can accumulate up to 292 million m^3 and has a watershed of 1,533 km^2. Both reservoirs have Nile tilapia production activities in net cages.

Climatic and hydrological characteristics

The region where the reservoirs are located has semi-arid conditions with a predominant BSW'h' climate, according to Köppen classification, characterizing a hot and semiarid

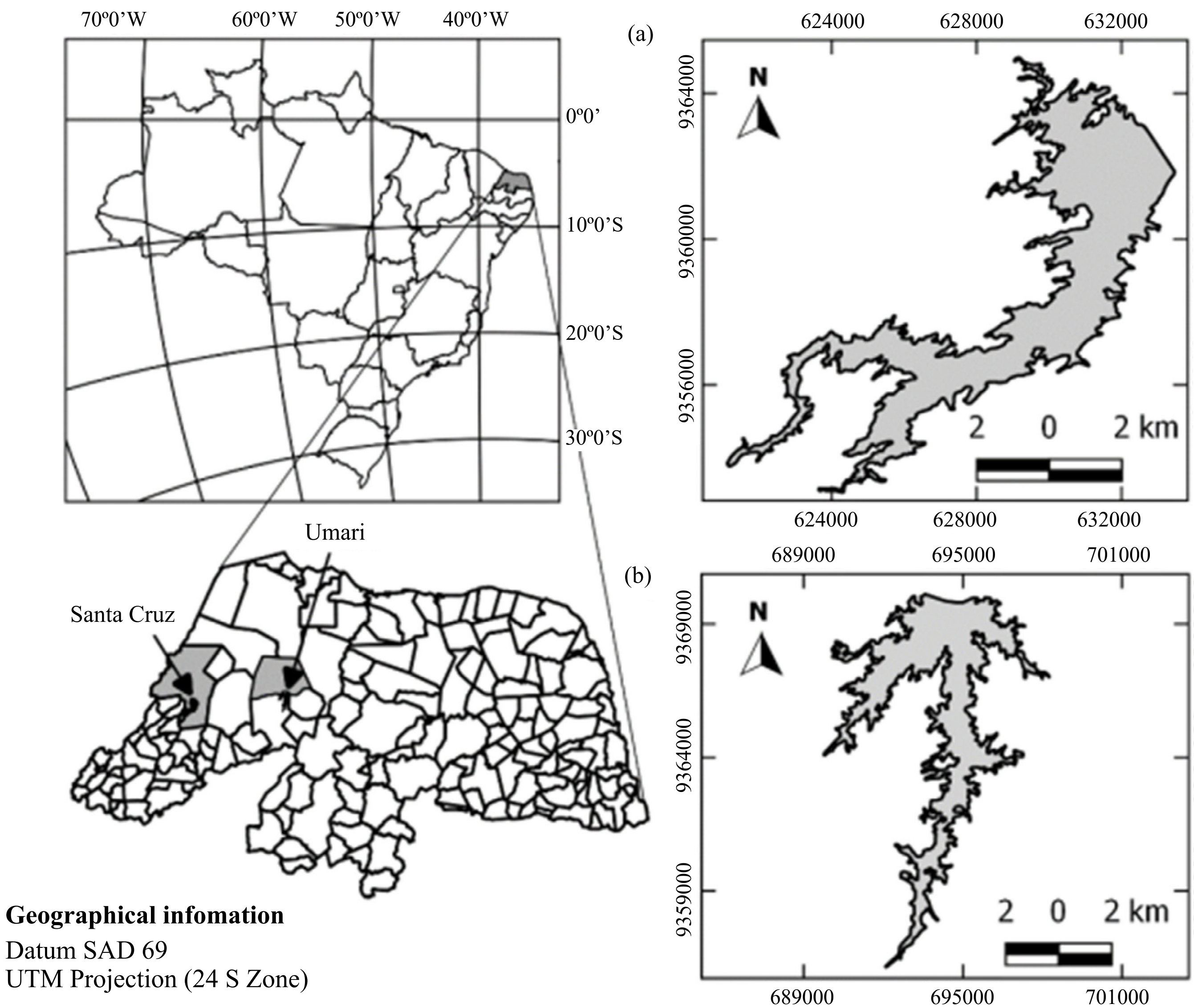

Figure 1. Santa Cruz (a) and Umari (b) reservoirs, located in the Brazilian semi-arid region.

climate with an average annual temperature of 28.5°C (minimum of 22°C and maximum of 35°C). Rainfall values in the reservoir watersheds were obtained from a climatological station monitored by the National Water Agency, located at coordinates 05°55'44.70"S/038°02'47.56"W. The Secretariat of the Environment and Water Resources (Secretaria do Meio Ambiente e Recursos Hídricos) of Rio Grande do Norte state provided the monthly data concerning the volume of Santa Cruz and Umari. The Deciles method was applied to classify the analyzed periods as submitted to drought or rain (Gibbs & Maher, 1967) based on rainfall data for the last 26 years in the reservoir watersheds. This method groups monthly rainfall occurrences in deciles (tenths of the data distribution), dividing the rainfall series into 10 equal parts in ascending order, from the lowest to the highest rainfall. Classification by the Deciles method ranges from very wet, wet, close to normal, severe drought, and extreme drought.

Total phosphorus concentrations

Previous studies have measured tilapia production, feed supplied, phosphorus contents in the tilapia diet and harvested biomass, and phosphorus concentration in reservoirs' water column (Cacho, 2017; Moura et al., 2016). Quarterly collections were performed between 2012 and 2014 in Santa Cruz (Moura et al., 2016) and 2015 and 2016 in Umari (Cacho et al., 2020). Surface water samples were collected in six sampling stations along each reservoir in each expedition, from the region near the dam to the region of lotic influence. In the samples obtained in the Santa Cruz reservoir, total phosphorus in the diet and fish biomass was measured according to Eaton et al. (2005), method 4500 P-B3. For the Umari reservoir, the phosphorus content in diet and tilapia biomass was estimated based on the rates described by Boyd et al. (2007). The amount of phosphorus released to the reservoir was calculated based on the difference between the amount of phosphorus added to the feed and the amount recovered in fish biomass. The masses of phosphorus released by the farming systems were standardized to one tonne of tilapia produced. Total phosphorus concentrations in the water column were determined following the method of Golterman et al. (1978).

Mass balance models

Mass balance models were constructed to calculate the phosphorus assimilation capacity in each reservoir. This study considered the maximum phosphorus load the reservoir could receive from fish farming without raising the concentrations of this nutrient above the reference limits. The first reference limit considered was the maximum phosphorus concentration allowed by national legislation for fish farming activities in reservoirs in Brazil, *i.e.*, 30 $\mu g \cdot L^{-1}$ (Brasil, 2005). The second reference limit was based on the premise that reservoirs in semiarid regions can withstand a concentration of inorganic phosphorus equal to 60 $\mu g \cdot L^{-1}$ before being considered eutrophic (Thornton & Rast, 1993).

A mass balance model for phosphorus was used to estimate each reservoir's phosphorus assimilation capacity (Dillon & Rigler, 1974). This model offers some advantages, such as the developing different phosphorus load scenarios, which is helpful in assessing the impacts of aquaculture activities and for being a model adapted to different aquatic environments. The model considers that the average annual concentration of total phosphorus in a reservoir is determined by the phosphorus load received (L), reservoir volume (V), area (A), average depth (Z), water renewal rate (E), and phosphorus retention coefficient in the reservoir (R). The model can be described in a balanced state as Eq. 1:

$$TP = \frac{L(1\text{-}R)}{(Z.E)} \quad (1)$$

Where:TP: total phosphorus concentration in the reservoir ($\mu g \cdot L^{-1}$); L: phosphorus load from fish production in net cages ($g \cdot m^{-2} \cdot year^{-1}$); R: phosphorus retention coefficient (dimensionless); Z: average depth of the reservoir (m); E: water renewal rate ($year^{-1}$). The final unit of the equation, originally expressed as $g \cdot m^{-3}$, was converted to $\mu g \cdot L^{-1}$, considering that 1 $g \cdot m^{-3}$ = 1 $mg \cdot L^{-1}$ = 1000 $\mu g \cdot L^{-1}$.

The means of these parameters were used as input data throughout the collection period in each reservoir. The renewal rate E was calculated using the volumes and effluent flow of each reservoir in each relevant collection month. These data were obtained from the Department of Environment and Water Resources of Rio Grande do Norte. The average depth was obtained through the ratio between the volume and the area of the reservoir in each month of phosphorus sample (Eq. 2):

$$Z = V/A \quad (2)$$

Thus, the average reservoir depth was obtained for each reservoir in each year of the study, and the mean of these values was used to determine the final model. The water renewal rate (E) for each year was calculated by dividing the annual water effluent flow (Q) by the average volume of water in the reservoir that year, according to Eq. 3:

$$E = 31536000Q/V \quad (3)$$

Where: Q: measured in $m^3 \cdot s^{-1}$; 31536000: the C conversion factor from $m^3 \cdot s^{-1}$ to $m^3 \cdot year^{-1}$; V: reservoir volume (m^3).

We calculated the value of the phosphorus retention coefficient (R) based on the renewal rate E (Beveridge, 2004), according to Eq. 4:

$$R = 1/(1 + 0.614\ E^{0.491}) \quad (4)$$

The primary equation can be rewritten from the original model to estimate the phosphorus load (L) required to raise phosphorus concentrations in the reservoir water to the considered reference limits of 30 and 60 $\mu g \cdot L^{-1}$. The following modified equation was obtained (Eq. 5):

$$Lmax = \frac{(\Delta TP.Z.E)}{(1\text{-}R)} \quad (5)$$

Where: Lmax: maximum phosphorus load from fish farming to the reservoir ($g \cdot m^{-2} \cdot year^{-1}$); ΔTP: maximum allowed increase in phosphorus concentration ($\mu g \cdot L^{-1}$); Z: average depth of the reservoir (m); E: water renewal rate ($year^{-1}$); R: phosphorus retention coefficient (dimensionless). To ensure consistency in the equation, the unit of ΔTP (originally expressed as $\mu g \cdot L^{-1}$) was converted to $g \cdot m^{-3}$.

In Eq. 5, the maximum phosphorus load is expressed in mass per area. Thus, the mass of phosphorus potentially originating from the fish farms was multiplied by the water surface of each reservoir to obtain the maximum amount of phosphorus to be released in that environment over a year to reach the reference limit values. Thus, the carrying capacity was calculated by Eq. 6:

$$CC = \frac{(L.A)}{\Delta P} \quad (6)$$

Where: CC: carrying capacity (tonnes tilapia·year^{-1}); L: phosphorus load from fish farming to the reservoir (kg.m^{-2}·year^{-1}); A: reservoir water surface area (m^2); ΔP: difference between the amount of phosphorus added as feed and the amount of phosphorus removed in the biomass of harvested fish per tonne of fish produced per year (kg P·tonnes tilapia^{-1}·year^{-1}).

Mass balance models were developed based on these equations, estimating the maximum fish biomass produced in each reservoir that will cause an increase of up to 30 and 60 µg·L^{-1} in the current phosphorus concentrations in the water column of the Umari reservoir and up to 60 µg·L^{-1} in the water column of the Santa Cruz reservoir. The maximum fish biomass that would increase by up to 30 µg·L^{-1} in Santa Cruz was not calculated, since phosphorus concentrations in this reservoir were above this limit. The applied models consider hydrological data to estimate the phosphorus assimilation capacity and the respective carrying capacity of tilapia rearing in reservoirs. The increments in total phosphorus concentrations in each reservoir were simulated using the Monte Carlo technique to consider the natural variability of each parameter of the model so that each parameter's uncertainty could be considered. This approach allows the creation of a set of possible values for each parameter. It recalculates the model for each set of values, thus generating a probability distribution of possible increments in the phosphorus concentrations.

After determining the maximum phosphorus loads, the other parameters of the model (Z, E, R, and A) considered random variables of uniform distribution (rectangular). The variables can assume any value between the maximum and minimum limit in the uniform distribution, considered in this study as the amplitude of each parameter, calculated for each reservoir during the entire collection period. Thus, 10,000 iterations were made, which means that the model was recalculated 10,000 times for each reservoir, using the new values generated for each parameter, thus obtaining a set of possible concentrations of total phosphorus in each reservoir and the probabilities associated with each one.

RESULTS

The region was subjected to a shortage of rainfall during the collection years (Fig. 2). The sampling period was classified as a severe drought season (average annual rainfall of ~464 mm). There was a progressive decrease in the volume accumulated by

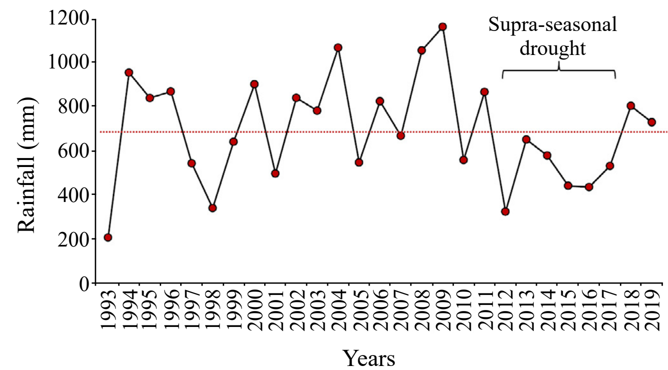

Figure 2. Annual accumulated rainfall (1993 to 2019) from a monitoring Apodi-Mossoró River Basin. Red dashed line corresponds to the average rainfall in the river basin from 1993 to 2019 (693 mm). The period from 2012 to 2017, in which a supra-seasonal drought was detected in the Apodi-Mossoró River Basin, is highlighted.

the reservoirs with the prolonged drought (Fig. 3). The levels decreased to 42% of the maximum storage volume in Santa Cruz and 36% in Umari at the end of the sampling period (2014). The average volume of the reservoirs concerning their total for the entire collection period was 50% (340 million m^3) in

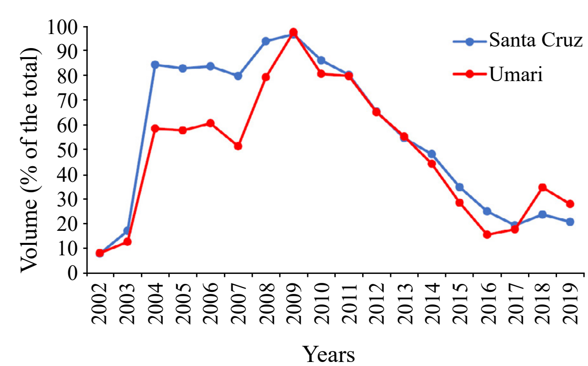

Figure 3. Volume (percentage of the total) of the Santa Cruz and Umari reservoirs from 2002 to 2019. Both reservoirs began to be filled in 2002.

Santa Cruz and 45% (153.6 million m^3) in Umari. The flooded area and average depth parameters decreased along with the accumulated water volume. The average effluent flow was higher in Santa Cruz (1.05 m^3·s^{-1}) than in Umari (0.91 m^3·s^{-1}), (Table 1).

The rate of water renewal was almost the double in Umari (0.19) when compared with Santa Cruz (0.10). Phosphorus retention decreased with greater water renewal (shorter residence time), causing a lower coefficient R in Umari (0.79) than in Santa Cruz (0.84) (Table 1).

Table 1. Parameters of the phosphorus carrying capacity model obtained for Santa Cruz and Umari reservoirs. Standard deviations are in parentheses.

Parameter	Santa Cruz	Umari
Flooded area (10^6 m^2)	22.7 (2.6)	18.9 (2.5)
Volume (10^6 m^3)	340 (63.6)	153.6 (25.4)
Average depth (V/A m)	14.9 (1.2)	8.1 (0.5)
Efluent flow ($m^3 \cdot s^{-1}$)	1.05 (0.4)	0.91 (0.1)
Water renew rate	0.10 (0.01)	0.19 (0.01)
Phosphorus retention coefficient	0.84 (0.01)	0.79 (0.01)

Fish farming in net cages produced 33 t/year^{-1} of Nile tilapia in Santa Cruz (Moura et al., 2016) and 281 t/year^{-1} in Umari (Cacho et al., 2020) during the period of the present study. Phosphorus releases from fish farming systems were 8.6 kg·t^{-1} in Santa Cruz and 9.1 kg·t^{-1} in Umari (Moura et al., 2019). These productions would correspond to a 1.4 and 18.9 mg·L^{-1} increase in total phosphorus concentrations in the water column of each reservoir, respectively. The Santa Cruz reservoir assimilation capacity was 5,848 kg·year^{-1} to reach the phosphorus concentration of 60 μg·L^{-1} in the water column. The phosphorus assimilation capacity in Umari was 573 kg·year^{-1} to reach the phosphorus concentration of 30 μg·L^{-1}, and 4,620 kg·year^{-1} to reach 60 μg·L^{-1}. The carrying capacity for Nile tilapia production in net cages in the Santa Cruz reservoir was estimated in 680 tonnes of phosphorus for reaching of 60 μg·L^{-1}. In contrast, at Umari, the carrying capacity was 63 tonnes in the 30 μg·L^{-1} scenario and 508 tonnes in the 60 μg·L^{1} one.

The Monte Carlo simulation estimated the probabilities of occurrence of final concentrations of total phosphorus with 10,000 iterations, for both reservoirs, with probability of occurrence (risk) of 5 and 10% (Fig. 4). In the 30 μg·L^{-1} scenario, there is a 10% chance of concentration being 32 μg·L^{-1} in Umari, while for Santa Cruz this cannot be calculated, as the reservoir concentration already exceeded the limit of this scenario. In the 60 μg·L^{-1} scenario, there is a 10% risk that total phosphorus concentrations will reach 73 μg·L^{-1} in the Santa Cruz and Umari reservoirs.

DISCUSSION

Modelling revealed that Santa Cruz reservoir can receive more phosphorus than Umari reservoir, considering the previously defined increment limit. Both reservoirs have similar water renewal rates. However, Santa Cruz remained with a higher volume during the analyzed period. The volume of stored water and water renewal were the variables that most influenced the models since the estimates consider morphometric parameters and internal rates of the reservoirs. The phosphorus retention rates calculated in the present study were 0.8, indicating that the reservoirs retain approximately 80% of the input phosphorus. This value is consistent with what is expected for reservoirs with low water renewal and high residence time (Straskraba, 1996). The water output is limited in periods of prolonged drought, given that the flows are regulated according to water availability, reflecting low renewal rates and high phosphorus retention coefficients.

Reservoirs can be considered nutrient traps, given that these water bodies store part of the compounds they receive from their tributaries, decreasing the amount of nutrients and other elements that reach the downstream sections. The retention of these elements occurs mainly by the biochemical pathway, caused by the chemical and biological oxidation of the compounds, and the physical pathway, resulting in sedimentation, which occurs with greater intensity in lentic and hybrid environments (Cunha-Santino et al., 2017; Donald et al., 2015).

Although the flow is one of the primary parameters that influence the retention of nutrients in reservoirs, phosphorus is one of the most susceptible to retention and assimilation in these environments (Cunha-Santino & Bianchini, 2005).

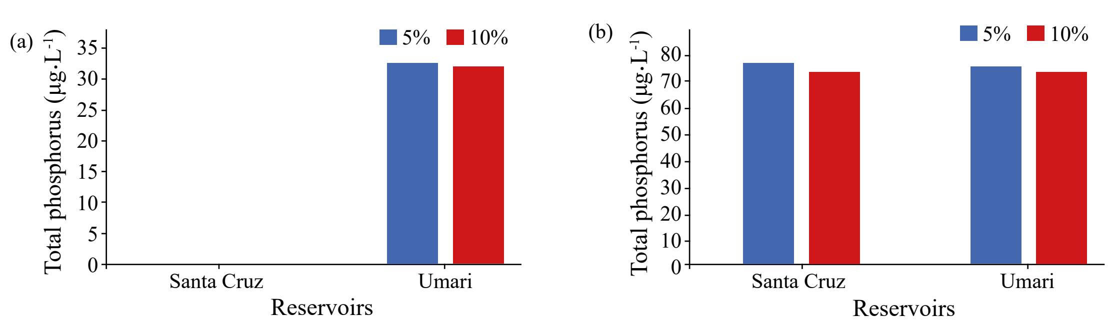

Figure 4. Probabilities (5 and 10%) of the final concentrations of total phosphorus being higher than expected in Santa Cruz and Umari reservoirs, in the two considered scenarios: (a) 30 μg·L^{-1}; (b) 60 μg·L^{-1}. In Santa Cruz reservoir, it was not calculated, since phosphorus concentrations were above this limit.

Both reservoirs studied presented similar average flows. Thus, other physical variables were probably determinants in the higher assimilation capacity observed in Santa Cruz compared to Umari. Physical parameters such as water volume, flooded area, and average depth have a positive relationship with the assimilation capacity of a water body. Therefore, there is a tendency for larger and deeper reservoirs to have greater capacities to assimilate incoming nutrients. Thus, Santa Cruz may receive more phosphorus than Umari before increasing its average phosphorus concentrations in the water column, due to its greater volume, flooded area, and average depth. In addition, the generation of the residue by farmed fish is also modified by the type of diet since excretions and concentrations in the feces of both phosphorus and nitrogen tend to be higher with a feed of high protein level and low quality/digestibility of protein and phosphorus (Chowdhury et al., 2013).

Nutrient assimilation rates tend to be higher in tropical reservoirs, mainly due to higher average annual temperatures. In these environments, the assimilation of compounds such as phosphorus occurs mainly by physical processes (sedimentation) and not biological ones (incorporation by phytoplankton) This phosphorus retention is intensified in reservoirs of semiarid regions, where high evaporation and low rainfall can lead to high residence times (Moura et al., 2014). The high residence time allows nutrients to remain in the reservoir for longer. Thus, a significant fraction is incorporated into the biomass of the biota or decants into the sediment, showing that morphometric and hydrological characteristics of reservoirs in semiarid climates may be determinant for water quality (Molisani et al., 2010).

Despite its importance, phosphorus assimilation capacity by itself is insufficient to determine a maximum acceptable level of fish farming. The magnitude of the impacts generated by the activity is another point to consider in managing these human-made lakes and should be studied locally. The models also disregard the other phosphorus sources that flow into the reservoir. Therefore, the calculated maximum production may be overestimated, especially if the other phosphorus contributions are unknown. In this sense, the continuous improvement of these models is essential, especially considering estimates of other sources of natural and anthropogenic phosphorus sources.

Considering the Brazilian legislation, reservoirs can only receive fish farming activities if their waters have total phosphorus concentrations up to 30 $\mu g \cdot L^{-1}$. Thus, Santa Cruz reservoir could not support fish farming activities, while Umari could support up to 62.9 $t \cdot year^{-1}$. On the other hand, the Umari reservoir could support tilapia production in net cages of up to 507.7 $t \cdot year^{-1}$, considering the maximum concentration of phosphorus in water up to 60 $\mu g \cdot L^{-1}$. In the same scenario, Santa Cruz could support the production of up to 680 $t \cdot year^{-1}$. However, exercising caution in increasing fish farming in these reservoirs is essential since these tropical man-made environments tend to remain thermally stratified for prolonged periods. Phenomena such as sudden rains can reduce the surface temperature of the water, and severe winds can promote vertical circulation in the water column and the consequent mortality of fish in net cages (Henry-Silva et al., 2019; Morais et al., 2010; Tundisi et al., 2010).

Due to global warming, there is a risk that semi-arid regions will become arid in the next century. In this context, the decrease in reservoir volumes in semi-arid regions, due to reduced rainfall and increased evaporation, may also contribute to the eutrophication process and proliferation of cyanobacteria, which would harm the multiple uses of reservoirs (Santos et al., 2016; Sherwood & Fu, 2014). In semi-arid regions, flood and drought regimes are extremely important in the structure and functioning of reservoirs, and there is a tendency for intensifying the eutrophication during dry periods (Bezerra et al., 2014; Molisani et al., 2010). Furthermore, the decrease in the volume and action of winds during dry periods facilitate the circulation of the water column, favoring an increase in nutrient concentrations in the reservoirs' water column, originating from the hypolimnion, and limiting the expansion of fish farming.

There is a risk that total phosphorus concentrations may exceed the reference values considered in the modelling, due to the natural annual variability of the hydrological parameters of each reservoir, such as accumulated volume and average depth, which in turn reflect on water renewal and, consequently, on the phosphorus retention rate. In this context, the risks of higher increases of this nutrient are similar between reservoirs, with phosphorus increments reaching values above those predicted by the models, raising the trophic level of these artificial aquatic environments. Risk estimation can be an essential tool in managing aquatic environments, as noted by Charlton et al. (2018), who calculated the risk of increasing total phosphorus concentrations in rivers, mainly due to climate change and, consequently, changes in the hydrological regimes of these environments.

We acknowledge the importance of model validation for ensuring predictive accuracy, as highlighted in previous studies (Gim et al., 2020; Yadav et al., 2022). However, historical data for traditional validation processes are unavailable in this study. We adopted a Monte Carlo simulation approach to address this limitation and estimate the probability of phosphorus concentration outcomes under different risk scenarios.

While this method provides a robust probabilistic framework, future research should focus on collecting diverse datasets and applying cross-validation techniques to enhance empirical models' generality and predictive accuracy in semi-arid reservoirs. In all scenarios considered in both reservoirs, there is a risk of phosphorus enrichment in the water column, which exceeds the maximum values predicted by mass balance models.

In the present study, the chance of the final total phosphorus values exceeding the expected by more than 10 $\mu g \cdot L^{-1}$ in some scenarios was observed, with probability of 10%. This unforeseen load of phosphorus in the mass balance can worsen the eutrophication process in these aquatic environments. In this context, the use of empirical models, which add information on local hydrology and the efficiency of the production system, is essential for evaluating scenarios and making decisions in public water management.

CONCLUSION

This study underscores the value of a probabilistic framework for assessing fish farming impacts in data-limited scenarios, a common challenge in Brazil. In semi-arid reservoirs, drought-induced water reductions heighten eutrophication risks, making carrying capacity estimation crucial. Given their multiple uses, studies should assess all human activities performed in the reservoirs to provide scientific-based information to regulate the different uses and enterprises. Therefore, it is possible to avoid reservoir eutrophication and allow their harmonic, and sustainable utilization. Expanding data collection will enhance these assessments and support more effective environmental management.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

All datasets were generated or analyzed in the current study.

AUTHORS' CONTRIBUTION

Conceptualization: Moura, R.S.T., Henry-Silva, G.G.; **Investigation:** Moura, R.S.T., Henry-Silva, G.G.; **Data curation:** Moura, R.S.T.; **Formal Analysis:** Moura, R.S.T., Angelini, R., Oliveira, N.P.M., Valenti, W.C., Henry-Silva, G.G.; Validation, **Writing – original draft:** Moura, R.S.T., Angelini, R.; **Writing – review & editing:** Angelini, R., Oliveira, N.P.M., Valenti, W.C., Henry-Silva, G.G.; **Resources:** Henry-Silva, G.G., **Supervision:** Henry-Silva, G.G.; **Final approval:** Henry-Silva, G.G.

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