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EARLY SIGNS OF EUTROPHICATION IN ONE OF THE FEW REMAINING OLIGOTROPHIC LAKES IN NORTHEASTERN BRAZIL:INSIGHTS FROM BONFIM LAKE

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ABSTRACT

The increasing demand for water supply, combined with poor land management around freshwater bodies, has threatened aquatic ecosystems. The Bonfim lake, located in the south of the municipality of Natal (RN, Brazil), is a coastal lake that has been used both as water source and as a site for leisure, with impacts on its water quality that are still little understood. This study aimed to monitor the water quality of the Bonfim lake between 2014 and 2016, and to assess changes in land use and cover in its subwatershed from 1985 to 2023. Sampling was conducted at three points (P1, P2, and P3), assessing key physical, chemical, and biological parameters. No significant differences were observed among the points, except for temperature and transparency, which were slightly higher at P2 and P1, respectively. These findings indicate that the lake is a spatially homogeneous environment, as is typical of well-mixed coastal lakes. Monitoring revealed a trend of increasing chlorophyll-a alongside reductions in total dissolved nitrogen and transparency over time. Publicly available data from the long term Água Azul Program indicated an increase in total phosphorus concentration during the same period, but a decrease in chlorophyll, a result that appears to contradict our findings. These changes coincided with the period (2010-2020) of dramatic expansion of agriculture and urban areas, loss of natural vegetation, and an episode of El Niño. The results indicate early signs of eutrophication in this important oligotrophic coastal lake starting around a decade ago. Our findings draw attention to the need for continuous water quality monitoring and sustainable management, as the Bonfim lake represents one of the main freshwater sources and one of the few remaining oligotrophic lakes in the state of Rio Grande do Norte. Finally, early detection of the eutrophication trends is essential for watershed management adjustments.

Keywords: Trophic state. Artificial eutrophication. Chlorophyll-a. Transparency. Total phosphorus.

1 Introduction

Inland aquatic ecosystems are important for human life, as they are exploited for multiple uses, such as leisure, agriculture, water supply, and the discharge of effluents from various sources (Tundisi & Matsumura-Tundisi, 2008; Esteves et al., 2008). Ironically, their intensive use has made them the world's most impacted ecosystems (Mammides, 2020). Rapid population growth increases both the demand for water and the production of waste in the form of domestic, industrial, and agricultural sewage, which is often released directly, without prior treatment, into rivers and lakes. It also increases watershed transformation, i.e. the shift from native vegetation to anthropized areas (Nobre et al. 2020). As a result, large loads of various nutrients, such as phosphorus (P), carbon (C) and nitrogen (N) become available in the water column, resulting in sanitary and ecological degradation through the process of artificial eutrophication (Tundisi & Matsumura-Tundisi, 2008; Von Sperling et al., 2008).

Artificial eutrophication of aquatic ecosystems occurs when ecosystem productivity increases due to excessive nutrient enrichment of anthropic origin, causing structural changes in planktonic communities and environmental metabolic imbalances (Esteves, 2011). This process disrupts the natural spatiotemporal patterns of limnological variables essential for ecosystem homeostasis. Consequently, it compromises water quality for consumption, irrigation, and aquaculture, as well as the potential for tourism, landscape quality, and overall quality of life, especially in areas with rapid urban expansion.

Investigating and understanding the behavior of limnological variables that regulate lake ecosystems is essential to ensure the health of the ecosystem and the populations that depend on it. The growing number of eutrophic aquatic bodies in recent years highlights artificial eutrophication as a global issue (Le Moal et al., 2019), which calls for long-term monitoring water quality in lakes, rivers, and reservoirs. Monitoring can provide early indications of eutrophication and improve understanding of local mechanisms that may be causing it, thereby supporting the management of water resources and restoration of water quality (Bezerra-Neto & Pinto-Coelho, 2002; Alves et al., 2012; Bem et al., 2013; Ganguly et al., 2015).

Coastal lakes have historically been subject to urbanization and population pressure (Zhou et al., 2022). In northeastern Brazil, coastal lakes in the state of Rio Grande do Norte face constant pressure due to multiple uses and poor land management, as exemplified by the Bonfim lake on the southeastern coast of the state. This lake is the largest natural water reservoir on the eastern side of the state and it is used for tourism, navigation, urban occupation, and crop irrigation (Melo et al., 2000; Cunha et al., 2014). It is also critical for human water supply via the Agreste Trairi Potengi pipeline system, which serves thirty cities and dozens of rural communities across a semi-arid region (ANA, 2021).

Lakes in northeastern Brazil suffer high rates of evaporation and domestic sewage input, making them more prone to accelerated eutrophication (They et al., 2017; Menezes et al. 2025). These factors highlight the importance of monitoring temporal patterns of water quality in aquatic bodies, especially in the few oligotrophic lakes. The Bonfim lake has been studied over the last decade, including assessments of water withdrawal impacts and hydrogeological studies (Duarte, 1999; Pereira et al., 2003). Melo et al. (2000) showed that the western sector of the lake yields the most water due to drilling of wells. Although some studies suggest a possible oligomesotrophic state (Duarte, 1999), the lake is generally classified as oligotrophic (They et al., 2017; Junger et al., 2019). Recent observations have documented unregulated development around the lake, including urbanization of recharge areas and replacement of native vegetation with agriculture (Santos, 2022). However, there are few studies that examine water quality in the lake, mainly regarding nutrient concentrations and variations over time, as well as long-term changes in land use and cover. One of the few available sources is the *Programa Água Azul* (Blue Water Program, https://programaaguaazul.ct.ufrn.br/), which provides public available data about water quality in water bodies of the state of Rio Grande do Norte. The main aim of this study, therefore, was to assess the water quality of the Bonfim lake, focusing on trophic state indicators from approximately ten years ago. To achieve this, we conducted monthly monitoring over a two-year period, to understand the behavior of key water quality variables. To place the observed trends in a broader temporal context, we also examined publicly available data from the Programa Água Azul and land use and cover in the subwatershed of the lake using the whole Mapbiomas series (1985-2023).

2 Materials and methods

2.1 Study area

The study was carried out in the Bonfim lake, located in the state of Rio Grande do Norte (Figure 1) south of the municipality of Natal, the state capital. Sampling was carried out monthly from May 2014 to February 2016, totaling 22 sampling events. Samples were collected at three points, selected to represent morphological variation within the lake: Point 1 (P1): 6°1'10.25" S / 35°11'40.6" W; Point 2 (P2): 6° 2' 18.4" S / 35° 12' 50" W and Point 3 (P3): 6° 3' 2.4" S / 35° 12' 11.15" W (Figure 1). The average depths at points 1, 2, and 3 over the monitoring period were 14 m, 13 m, and 16 m, respectively. The lake has a surface area of 9 km², and capacity of 84 million m³, consisting of three interconnected bays. The mean depth is 11.39 ± 4.05 m, with a maximum of 25 m and a minimum of 5 m. The climate is humid tropical due to the lake's proximity to the coast (SUDENE, 1990). Recharge occurs through two sources: rainfall and subsurface flow from the dune-barrier aquifer (Pereira et al., 2003).

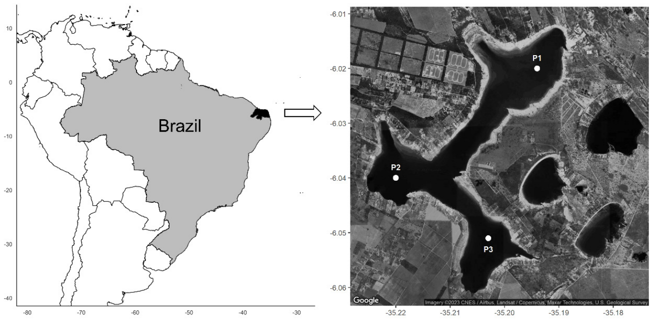

Figure 1. Bonfim lake location in northeastern Brazil and sampling points (P1-P3).

2.2 Field and laboratory analysis

Water samples were collected monthly at the three sampling stations using a Van Dorn bottle at a depth of one meter, always in the morning. The samples were stored in polyethylene gallons and transported to the Limnology Laboratory at the Federal University of Rio Grande do Norte within four hours. In the field, measurements were taken of water temperature (°C), pH, conductivity (mS cm^{-1}), and dissolved oxygen (mg L^{-1}) using a HORIBA multiparameter probe (model U-22). Water transparency (m) was measured with a 30 cm diameter Secchi disk. Subsurface samples (approximately 10 cm depth) for alkalinity (μEq L^{-1}) were collected in polyethylene bottles without headspace.

In the laboratory, alkalinity was determined immediately, using the Gran titration method with 0.0125 M H_2SO_4. Variable volumes of water were filtered through glass fiber filters (Whatman, GF/C, 1.2 μm mean pore size) for chlorophyll *a* (Chl*a*, μg L^{-1}) analysis. Chl*a* was extracted with 90% ethanol at -20°C for up to 24 hours. After extraction, samples were centrifuged for 20 minutes at 3500 rpm and absorbance was read at 665 nm, with turbidity correction at 750 nm, using a Quimis spectrophotometer (Nusch & Palme, 1975; APHA, 1999). Concentrations were calculated following Salonen & Sarvala (1995) and Schilling et al. (2006).

Filtered water (< 1.2 μm) was stored in 25 mL borosilicate vials, previously baked at 450 ºC (> 3h) in a muffle furnace, for analysis of total dissolved nitrogen (TDN, μM) and total dissolved organic carbon (DOC, μM). Samples were acidified with 100 μL of concentrated sulfuric acid and refrigerated until analysis. TDN was quantified by chemiluminescence, and DOC by the Non-Purgeable Organic Carbon method (NPOC) using infrared spectroscopy in a Shimadzu TOC-V total organic carbon and nitrogen analyzer, with synthetic air (5.0 FID) as the carrier gas.

Filtered samples for the analysis of total dissolved phosphorus (TDP, μM) were stored in polyethylene bottles and frozen (-20ºC) until analysis. Samples were digested in an autoclave by oxidation at 121 °C for 30 minutes in the presence of alkaline potassium persulfate (Carmouze, 1994) and analyzed by the ascorbic acid method (Mackereth et al., 1978).

2.3 Publicly available data

Due to the limited available information on the water quality of Bonfim lake, we also examined data from the *Programa Água Azul* (http://programaaguaazul.ct.ufrn.br/), a joint initiative between academic and state institutions that monitors the water quality of major ground and surface water bodies in Rio Grande do Norte. For Bonfim lake, semi-annual data are available from 2008 to 2016 for a single sampling point located near the state water supply company building (Adutora Monselhor Expedito - CAERN) and close to our monitoring point P2. For our purpose, we extracted data on total phosphorus (TP, mg L^{-1}) and chlorophyll *a* (chl*a*, μg L^{-1}).

2.4 Trophic state index

Trophic state indices were calculated for both datasets using the modification of Carlson's Trophic State index proposed Toledo Jr. (1990) based on available measurements of chlorophyll *a*, total phosphorus, and transparency (Supplementary Tables 01-02).

2.5 Land use and cover

The surroundings of Bonfim lake were determined using the Global Watershed web application (Heberger, 2022), which defines the immediate upstream subwatershed based on a user-defined point in the map. This was used as an objective and natural criterion for detecting the most immediate influences on the lake. We retrieved long-term annual data (1985 to 2023) from the MapBiomas project "Land use and cover" product, Collection 9, which provides pixel-level classification based on satellite imagery (https://brasil.mapbiomas.org/ - Souza et. al., 2020) -

The following categories were selected for analysis: natural vegetation, non-vegetated areas, agriculture, mosaic of uses, urban area, water, and dune. The dune category was excluded from the temporal trend analysis (Mann-Kendall analysis), due to its negligible representation in the time series (< 3%).

2.6 Data analysis

Comparisons among sampling points (P1 × P2 × P3) were determined using Friedman test followed by Conover's multiple comparison test with Bonferroni correction. Since no significant differences were found for the environmental variables, except for temperature and transparency (Table 1), the three sampling points were treated as replicates in subsequent analyses.

Table 1. Water quality variables at each sampling point during the monitoring of Bonfim lake. Data are mean ± standard deviation. Chla: Chlorophyll *a*; DOC: dissolved organic carbon; TDN: total dissolved nitrogen; TDP: total dissolved phosphorus.

Variables	Sampled points		
	P1	P2	P3
Temperature (°C)	27.61 ± 0.97 ^{b}	27.62 ± 1.18 ^{a}	27.58 ± 1.03 ^{b}
Dissolved oxygen (mg L^{-1})	5.79 ± 1.66	6.20 ± 1.88	6.15 ± 1.77
pH	6.29 ± 0.91	6.27 ± 0.64	6.32 ± 0.81
Conductivity (mS cm^{-1})	0.12 ± 0.04	0.11 ± 0.04	0.11 ± 0.04
Transparency (m)	5.42 ± 0.94^a	4.64 ± 1.16^b	4.65 ± 0.90^b
Alkalinity (μEq L^{-1})	153.53 ± 60.73	154.91 ± 61.53	145.96 ± 41.84
Chla (μg L^{-1})	0.74 ± 0.42	0.60 ± 0.48	0.64 ±0.48
DOC (μM)	125.80 ± 41.64	124.54 ± 50.52	126.15 ± 46.19
TDN (μM)	14.94 ± 14.71	9.72 ± 4.50	18.52 ± 33.78
TDP (μM)	0.51 ± 0.68	0.27 ± 0.14	0.44 ± 0.48

Due to the limited number of observations in the dataset, three-monthly moving averages (MA) were applied to smooth the data and identify general trends in water quality variables, total phosphorus, and chlorophyll *a* from the *Água azul* dataset. For chlorophyll *a*, missing values (87 months of data) were imputed using linear interpolation with the *na_interpolation* function from the *imputeTS* package (Moritz & Bartz-Beielstein, 2017). Seasonal effects were excluded due to insufficient data points to reliably model seasonality. Temporal trends in water quality and land use and cover (1985-2023) were analyzed using the modified Mann-Kendall test for autocorrelated data, implemented via the *modifiedmk* package (Patakamuri & O'Brien, 2021).

For all analyses, a statistical significance level of $\alpha = 0.05$ was adopted. Maps, graphs and statistical procedures were performed using R software, version 4.2.3 (R Core Team, 2023) with the following packages: ggmap (Kahle & Wickham, 2013), ggplot2 (Wickham, 2016), PMCMRplus (Pohlert, 2023), grid (R Core Team, 2023), devtools (Wickham et al., 2022), and mapproj (Brownrigg et al., 2023).

3 Results

All sampling points showed similar values for physical-chemical parameters, indicating homogeneity among the different areas of the lake, with the exception of temperature and transparency. Temperature was slightly higher at P2 than P1 and P3 (Table 1). Transparency was significantly higher at P1 than P2 and P3 (Table 1).

A significant increasing trend in chlorophyll *a* (Chl*a*) was observed over time (Table 2, Figure 2d), while total dissolved nitrogen (TDN) and transparency showed significant decreasing trends during the monitoring period (Table 2, Figure 2f and h). No significant trends were detected for the other limnological variables.

Data from the *Água Azul* Program indicated an increasing trend in total phosphorus (TP) concentration from May 2014 onwards. In contrast, chlorophyll *a* showed a decreasing trend, with peak values around 2009-2010 followed by a decline (Figure 3; Table 2).

The trophic state of the lake ranged from ultraoligotrophic to oligotrophic in both data sets. In the two-year dataset from this study, ultraoligotrophic conditions were more frequent in 2014 and less frequent in 2015, with no occurrences in the second half of that year (Supplementary Table 1). In the Água Azul dataset, the ultraoligotrophic state was detected only once in the initial report from 2008 and did not appear again in later records (Supplementary Table 2).

Table 2. Results of the modified Mann-Kendall test for the trend of temporal variation for water quality variables (n = 66) throughout the monitoring period, *Água Azul* monitoring program data, and land use and cover (n = 39 years) of Bonfim lake. The sign of corrected z-values indicates increasing (+) or decreasing (-) trend associated with the corrected *p*-values. Chl*a*: Chlorophyll *a*; DOC: dissolved organic carbon; TDN: total dissolved nitrogen; TDP: total dissolved phosphorus; TP: total phosphorus.

	z_{corr}	p-value$_{corr}$
Water quality		
Temperature (°C)	-0.72	0.477
Dissolved oxygen (mg L^{-1})	-0.62	0.533
pH	0.33	0.741
Transparency (m)	**-6.63**	**< 0.0001**
Alkalinity (µEq L^{-1})	-0.18	0.86
Chl*a* (µg L^{-1})	**5.23**	**< 0.0001**
DOC (µM)	1.48	0.138
TDN (µM)	**-3.71**	**< 0.001**
TDP (µM)	-0.70	0.485
Água azul monitoring program		
Chla (µg L^{-1})-	**-7.62**	**< 0.0001**
TP (mg L^{-1})	**2,11**	**0.0346**
Land use and cover		
Natural vegetation	**-6.03**	**<0.0001**
Mosaic of uses	0.35	0.729
Agriculture	**4.09**	**<0.0001**
Urban area	**6.23**	**<0.0001**
Non vegetated area	**4.32**	**<0.0001**
Water	**-7.49**	**<0.0001**

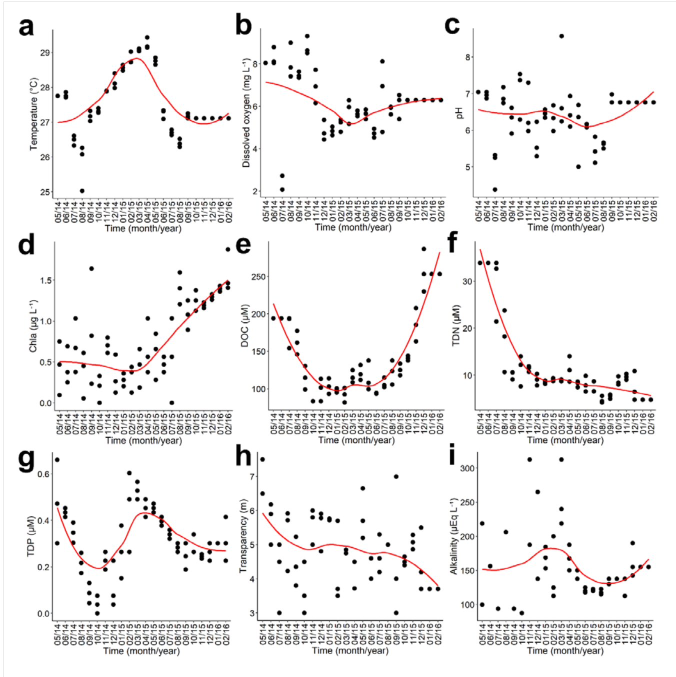

Figure 2. Temporal variation and 3-point moving average (red line) of temperature (a), dissolved oxygen (b), pH (c), chlorophyll *a* (chl*a*; d), dissolved organic carbon (DOC; e), total dissolved nitrogen (TDN; f), total dissolved phosphorus (TDP; g), transparency (h), and alkalinity (i) throughout the monitoring period of Bonfim lake. Trend fits are indicated by solid red lines.

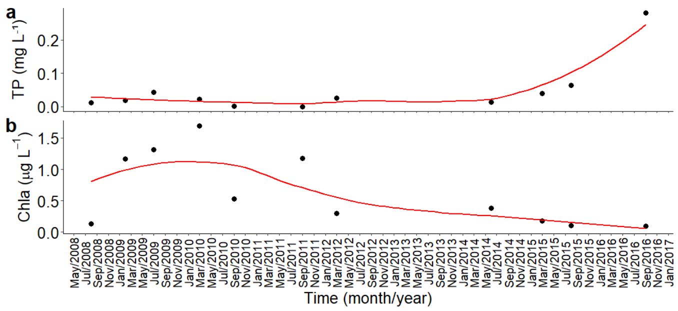

Figure 3. Temporal patterns and moving average (red line) of total phosphorus (TP) and chlorophyll *a* (Chl*a*) concentrations, collected from data provided by the *Programa Água Azul* for Bonfim lake.

Land use and cover data showed a strong reduction in natural vegetation and loss of lake area, accompanied by increases in non-vegetated, urban, and agriculture areas (Table 2). The most pronounced loss of natural vegetation occurred during the 1990's, while the urban and agriculture expansion was concentrated between 2010 and 2020 (Figure 4). Over four decades (2020 compared to 1990), natural vegetation decreased by more than 50%, lake area decreased by 22.7%, agriculture area increased by 4000% and urban area increased by 450%, including expansion into areas close to the lake (Figure 5). The mosaic of uses did not change significantly, with only a small decrease of 3% (Figures 4 and 5).

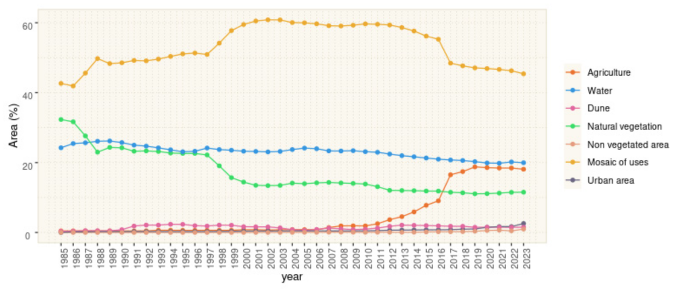

Figure 4. Time series of land use and cover from 1985 to 2023 for the immediate watershed of Bonfim lake.

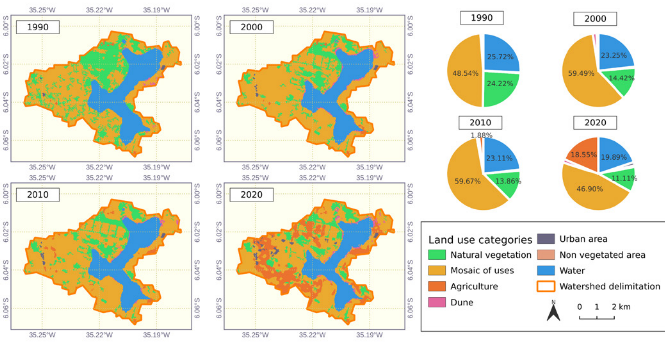

Figure 5. Change in land use and cover over four decades (1990-2020) for the immediate watershed of Bonfim lake.

4 Discussion

Lakes can be classified according to their trophic state, which is determined by indicators, such as chlorophyll *a*, nutrients concentrations, and water transparency (Schlesinger & Bernhardt, 2020). This classification ranges from ultra-oligotrophic (very low productivity) to hypereutrophic (very high productivity) (Schlesinger & Bernhardt, 2020). Based on these classic indicators, Bonfim lake was characterized as an (ultra)oligotrophic ecosystem, with low expected nutrient input and low organic production (Wetzel, 2001). However, our results point to a consistent increase in total phosphorus and chlorophyll *a*, as well as a decrease in transparency. These changes are likely associated with the pronounced changes in land use and cover, particularly in recent decades. This pattern may serve as an early warning of the need to revise lake management practices to maintain acceptable water quality.

Most natural lakes in Brazil are small and shallow (< 5m) (Padisák & Reynolds, 2003), with a few exceptions (Esteves, 2011). Coastal lakes are generally polymictic due to shallowness and wind mixing, and are often spatially homogeneous (Esteves, 2011), except in cases of marine intrusion, which can cause stratification of the water column (Genovez et al., 2024). Despite its depth, Bonfim lake showed spatial homogeneity, similar to other shallow coastal lakes. The magnitude of differences found for temperature are negligible and likely reflect statistical variation rather than biologically relevant gradients. Transparency was higher at P1 (~1m) than at other points, but this may have been influenced by inorganic particles, as no differences in chlorophyll *a* were detected. Standard deviations also overlapped across points. Given the similarity of most of the variables, and for analytical consistency, the dataset was treated as spatially homogenous. We believe that this approach supports the overall interpretation, as the observed patterns were very consistent. Therefore, the discussion focuses on temporal variation in water quality, particularly variables related to trophic state.

The monitoring period (2014 – 2016) coincided with an El Niño–Southern Oscillation (ENSO) event, which caused severe drought in the northeast region of Brazil (Marengo et al., 2017). This led to increased evaporation rates and water residence time in aquatic ecosystems, resulting in higher nutrient concentration (Menezes et al. 2025). These conditions may also explain the shrinkage in lake area, although excessive water withdrawal probably also contributed to this. The reduction in water volume through evaporation can lead to higher nutrient concentrations and promote eutrophication, as previously reported for coastal lakes (They et al. 2017), and this may partly account for the observed increase in total phosphorus.

In lakes, nutrient availability and light are key factors influencing phytoplankton productivity (Jia et al., 2020). Inorganic nutrients such as inorganic carbon, nitrogen, and phosphorus are converted into biomass by photoautotrophic organisms such as algae, cyanobacteria, and macrophytes, using solar radiation (Istvánovics, 2009). These nutrients originate from various sources, including the watershed. Another possible explanation for the increase in lake productivity over time is the presence of agriculture around the lake, which may contribute to nutrient input (Xu, 2008; Schlesinger & Bernhardt, 2020). Although data limitations prevented this association from being formally tested, there was a dramatic change in land use and cover over around this lake, particularly between 2010 and 2020. This period overlaps with both our monitoring and the *Água Azul* datasets, when the detectable changes in eutrophication indicators appear to correspond to reductions in natural vegetation and increase in urban, and agricultural areas. Previous studies reported that more than 81% of the lake surroundings are occupied by agriculture and pasture (Junger et al., 2019) and this proportion may have increased over the years. More recent studies indicate that the lake surroundings suffer from anthropic action, with the recharge area being primarily occupied by agriculture rather than by native vegetation (Santos, 2022).

It is important to note that our monitoring period had a cut-off period of just under two years, which restricts the ability to estimate trends that could detect long-term changes in trophic state of the lake. By incorporating data on surface waters from the *Água Azul* program, a longer temporal perspective was obtained (2008-2016). The dataset showed a four-fold increase in total phosphorus since 2014 and a three-fold decrease in chlorophyll *a* concentration after 2010 (Figure 3), which contrasts with the three-fold increase in chlorophyll *a* observed during the 2014-2016 monitoring period. It is important to take into account that the *Água Azul* data are more fragmented and may not capture short-term fluctuations. Additionally, they represent a single point (close to our P2), which may not reflect conditions across the whole lake. As a biological variable, chlorophyll *a* is subject to greater variability than many abiotic parameters, since phytoplankton is influenced by biological factors such as grazing, competition, and parasitism. A four-fold increase in total phosphorus in *a* (ultra)oligotrophic lake may have substantial ecological consequences, including increased phytoplankton productivity when other limiting factors are reduced. Overall, both datasets clearly indicate a consistent increase in phosphorus over time, particularly in recent years. This trend coincides with the El Niño period, and may result from the combined effects of agricultural and urban expansion, higher evaporation rates, and water withdrawal. Changes in climate patterns might intensify drought conditions, exposing lakes, such as the Bonfim, to prolonged water balance deficits (Marengo et al. 2017), further increasing nutrient concentrations and the risk of water quality deterioration.

Freshwater resources are limited and are increasingly affected by pollution, making them unfit for human consumption (Savenije & Van der Zaag, 2008). Despite its economic and ecological importance, data on water quality of Bonfim lake remain scarce and temporally fragmented. Although the results presented refer to conditions nearly a decade ago, the lake was already showing signs of eutrophication. This highlights the need for updated assessments and continuous monitoring to support effective watershed and water quality management. Reviewing the management of water resources is essential to prevent indiscriminate use of water and to preserve the ecological integrity of the environment through the responsible and sustainable use of available resources.

5 Conclusions

The monitoring results show that Bonfim lake is a spatially homogeneous environment and that it shows early signs of a shift toward eutrophication during the timespan analyzed. This trend may be associated with a combination of increasing anthropic pressure—through urbanization and the expansion of agriculture and urban areas around the lake—as elevated evaporation rates due to the El Niño event of 2014—2015. However, the relative influence of these factors remains uncertain. These findings are especially relevant in the context of human transformations in the natural landscape and ongoing climate changes. Our findings reinforce the need for continuous monitoring of the lake's trophic state to support regulation of water use, given that Bonfim lake is one of **the** principal sources of water in the state of Rio Grande do Norte.

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