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Assessing the effectiveness of management measures in the Ria Formosa coastal lagoon, Portugal

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The Ria Formosa is an important transitional and coastal lagoon on the south coast of Portugal that provides valuable ecosystem services. The lagoon is a protected area under national and international conventions. There is a great potential for Blue Growth sectors, such as aquaculture and coastal tourism, but these rely on good water quality. European environmental legislation, such as the Water Framework Directive, requires member states, such as Portugal to implement management measures if a surface water body is not of good ecological status. This work addresses the effectiveness of management measures, such as wastewater treatment plant implementation and dredging, on the water quality of the Ria Formosa coastal lagoon system. This is an important social-ecological issue, since management measures can be very expensive. The ecological status of Ria Formosa was evaluated, according to the physico-chemical and biological quality elements of the Water Framework Directive. The main indicators were the physico-chemical quality elements of nutrient and oxygen condition, and the biological quality element chlorophyll *a*, as a proxy for phytoplankton biomass, under the Water Framework Directive. The data for these quality elements from the Ria Formosa were analyzed for consistency with the classification for the Water Framework Directive water bodies. The data after the implementation of management measures was compared with historical data to evaluate if these measures had been effective. The relation between nutrient pressures, meteorological and hydrological conditions was addressed, especially rainfall and runoff. Results showed a decrease in nutrient concentration after the management interventions, despite the increase of population and intensifying agriculture in the catchment. The Ecological

Status is spatially variable with an overall moderate status, indicating the need for further management measures. There is a significant reduction in nutrient pressure on the lagoon during drought years. This indicates that climate change may alter the structure and function of the lagoon in the future.

KEYWORDS

Ria Formosa, coastal lagoon, assessment of management, Water Framework Directive, intercalibration sites

Introduction

An estimated 2.4 billion people live within 100km of the coast with 40% percent of the world's population living on only 4% the land area (United Nations [UN], 2017). This is partly because coastal ecosystems are among the most productive ecosystems in the world (Levin et al., 2001), providing 38% of the total value for ecosystem services (Costanza et al., 1997). For example, in Catalonia, 40.3% of the total annual flow of ecosystem service value is provided by the coastal zone, which accounts for only 22.2% of the total surface area (Brenner et al., 2010). Globally, fisheries and fish products provided 203 ± 34 million full-time equivalent jobs in 2011 (Teh and Sumaila, 2013). Thus, the long-term sustainability of coastal populations relies on ecosystems and the services they provide (Barbier et al., 2008), including the Ria Formosa lagoon in Portugal (Newton et al., 2018).

The growth of coastal populations is higher than the global average, with multiple human activities also increasing, such as fisheries, aquaculture, energy production, shipping, tourism and recreation. There are also increasing resulting pressures, such as inputs of effluents and runoff from agriculture, that become multi-stressors in the context of climate change (Guerry et al., 2012). An analysis of 12 temperate estuarine and coastal ecosystems in Europe, North America, and Australia (Lotze et al., 2006) showed that these have already been depleted of 90% of formerly important species, 65% of seagrass and wetland habitat has been destroyed, water quality is degraded, and there are accelerated species invasions. This is a result of the pressures on wetlands, such as coastal lagoons, at the global scale (Pérez-Ruzafa et al., 2019; Newton et al., 2020). Thus, successfully designing and implementing management measures in coastal lagoons is vital to secure the valuable ecosystem services that they provide. This is a challenging task given the strong and wide variety of human activities and resulting pressures on coastal lagoons.

The Water Framework Directive (WFD) is the EU legal framework for integrated river basin management, including transitional and coastal waters (European Community [EC], 2000). It requires member states, such as Portugal, to implement management measures, when a surface water body is not of good ecological status. This is an important social-ecological issue, since management measures, such as building and upgrading sewage treatment plants, can be very expensive. When such management decisions are taken, it is assumed that they will result in improved water quality. However, this may not be the case if inputs increase due to population increase or because of diffuse inputs from runoff. The hypothesis underlying this study is that management measures should improve the water quality of a water body. Although the study is not intended as an environmental report on WFD compliance, it is the legislative and regulatory context of the study.

The study site is the Ria Formosa coastal lagoon that extends 55km along the coast of southern Portugal (Newton et al., 2013). The catchment is approximately 864 km^2 (Duarte et al., 2008). The lagoon has local, national regional and international significance (Newton and Mudge, 2003; Newton et al., 2018). It is a Portuguese Natural Park, since 1987; a Special Protection Area of the EU Birds Directive, a site of Natura 2000 network (site code PTZPE0017); and the international Ramsar convention (site 212, since 1980). The Ria Formosa protects 121 species of the Nature Directives and protects 19 habitat types of the Habitats Directive, according to the European Nature Information System of the European Environment Agency.

The Ria Formosa is a well-studied system (Newton et al., 2013) with numerous publications detailing aspects of its hydrology (e.g., Roselli et al., 2013) and human pressures (Newton et al., 2020). Historical pressures on the Ria Formosa include damming of water courses, e.g., in the west Ancao Basin; consolidation of inlets, e.g., the main Faro channel inlet at Farol; saltmarsh reclamation for salt-extraction and aquaculture ponds as well as major infrastructures, such as the international airport of Faro and sewage treatment plants; and construction on the dunes (Newton et al., 2020). The human pressures are increasing with population increase in the Algarve, from ∼395000 in the 2001 census to 467000 in the 2021 census (Intituto National de Estatistica portal consulted on 30/08/2022[1]). The main threats now include erosion, storm

1 https://www.ine.pt/xportal/xmain?xpgid=ine_main&xpid=INE

surges and overtopping (Carrasco et al., 2021; Domingues et al., 2021); climate change (Brito et al., 2012b; Rodrigues et al., 2021); flooding and sea level rise (Lopes et al., 2022); sewage (Cravo et al., 2022a); eutrophication and hypoxia (Cravo et al., 2020); pharmacological contamination (Cravo et al., 2022b) and chemical pollution (Silva et al., 2021).

The illegal harvesting of high-value species such as seahorses and sea-cucumber, destined for foreign markets such as Asia, relies on local knowledge. Macrobenthos and fish are Biological quality elements of the WFD, so the systematic and illegal removal of species, such as sea-cucumbers, and sea-horses degrades the ecological status.

Good water quality for the Ria Formosa is important as the ecosystem services of the lagoon (Newton et al., 2018) support valuable economic activities such as shellfish harvesting, fishing, water sports, beaches and eco-tourism. Several environmental management measures have been implemented over three decades to improve the water quality of the western part of the lagoon. These include the installation (1989) and subsequent upgrade (2009) of Urban Wastewater Treatment plants (UWWT) and dredging (June 1997) of the Ancão Inlet.

Physico-chemical quality elements (e.g., nutrients, dissolved oxygen) and phytoplankton are commonly used for classification of water bodies in coastal waters (SWD, 2019). However, the Ria Formosa does not strictly fit the WFD definition of a coastal or transitional water body because of its salinity regime. Ferreira et al. (2005, 2006) defined the typology for the Ria Formosa as "sheltered coastal water" and identified 5 distinct waters bodies within the lagoon. Studies indicate that the tidal water exchange at the inlets result in both import and export of nutrients to and from adjacent coastal waters (Newton and Mudge, 2005; Cravo et al., 2013, 2014, 2015; Cravo and Jacob, 2019; Rosa et al., 2019).

The EU does not have generic WFD protocols for ecological status assessment of surface water bodies. It is left to the EU member states, according to the subsidiarity principle in the EU, to develop their own WFD surveillance monitoring protocols for coastal and transitional waters, provided that these protocols comply with the overall WFD and are intercalibrated within the eco-regions.

The WFD monitoring strategy for the surface waters in Portugal was developed during 4 national projects (SWD, 2015). The criteria for the selection of the monitoring stations that were used to select the stations in this study were designed to detect temporal changes in ecological status due to natural or anthropogenic factors and implemented according to Decree Law n° 77/2006. An intercalibration exercise, led by the European Union Joint Research Centre (JRC), was reported by Portugal to the European Environment Agency (EEA) by the Instituto da Água (INAG; Newton et al., 2007). Furthermore, the results were subsequently published in scientific journals (Nobre et al., 2005; Ferreira et al., 2006, 2007; Loureiro et al., 2006; Goela et al., 2009; Brito et al., 2010).

The philosophy and hypothesis underlying management measures is that these management measures are effective for the improvement of water quality. This paper assesses the effectiveness of different management measures in terms of the improvements to the ecological status of the Ria Formosa coastal lagoon within the context of the WFD, accounting for the spatial and temporal variability of abiotic factors and based on 5 research questions:

1. Are the WFD intercalibration stations (Ponte and Ramalhete) and the reference station (Praia) significantly different with respect to physico-chemical variables?
2. Has the water quality improved in the western section of the Ria Formosa?
3. What is the Ecological Status of the Ria Formosa in the context of the WFD, based on the physico-chemical supporting quality elements nutrients and oxygen condition, and the biological quality element phytoplankton biomass, using chlorophyll *a* as a proxy?
4. What is the relationship between rainfall, runoff and nutrient pressures, as this maybe relevant in a changing climate?
5. Are there significant differences in water quality between the lagoon and ocean indicating whether there is an overall export or import of nutrients?

Materials and methods

The protocols for analyses of coastal and transitional waters were based on the Portuguese implementation of the Water Framework Directive, led by the Portuguese water institute INAG (Bettencourt et al., 2003; Ferreira et al., 2003, 2005).

Sampling and sample treatment

The location of the various sampling sites in the Ria Formosa are shown in **Figure 1**, with the most intensive campaigns occurring at the sites shown within the inset rectangle in the figure. The numbering and names of the stations have varied in different projects, but the locations did not vary over time. Some stations were sampled throughout the period and some more sporadically. The GIS maps and data pooling were based on the coordinates of the stations.

The sampling and sample treatment are summarized below, with much more detailed descriptions provided in the relevant papers (see Introduction). Sampling and sample treatment was generally consistent over the various sampling campaigns between 1984 and 2012. Field *in situ* determinations included water temperature and salinity that were recorded in the field using a calibrated WTW® salinity/conductivity probe.

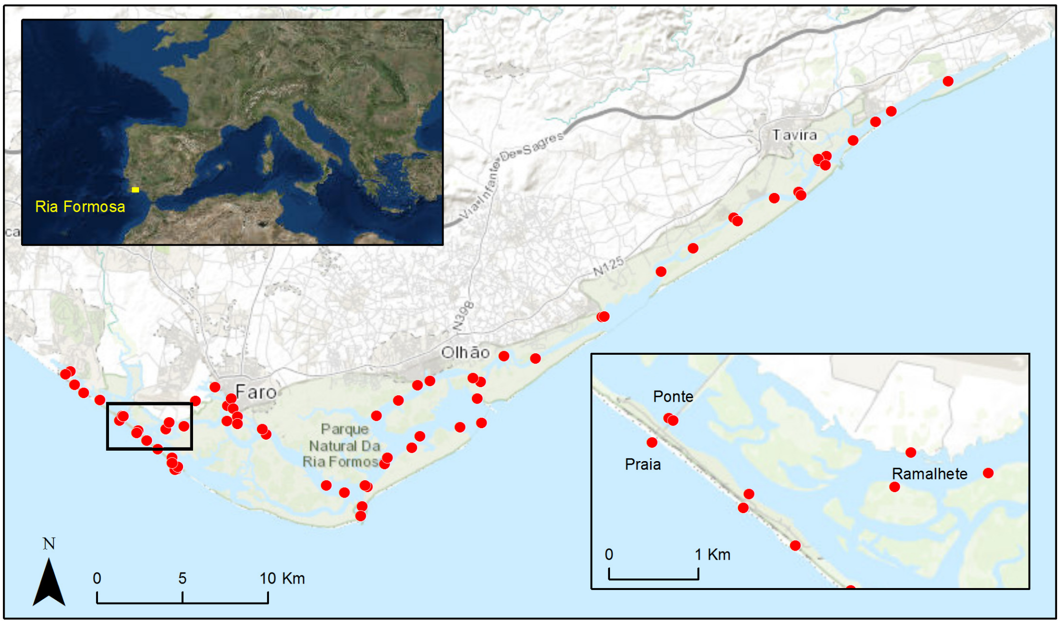

FIGURE 1
Map of the Ria Formosa lagoon, Portugal showing the main sampling stations. Inset _top left: geographical location of the lagoon; inset_bottom right: expansion of the rectangle at the western lagoon showing more intensively sampled stations, particularly Praia, Ponte and Ramalhete for the Water Framework Directive intercalibration.

Oxygen samples were fixed *in situ* for subsequent Winkler titration, modified by Grasshoff et al. (1999). Water samples of approximately 200 ml were collected for the analysis of nutrients (ammonium, nitrites, nitrates, phosphates, silicates); samples were stored in cool, dark boxes and subsequently frozen at −18°C in the laboratory until further analysis. Samples of 1 dm^3 of water were filtered through GF/F (47mm) filters and were kept frozen (−18°C) until further analysis for Chl*a*.

Laboratory determination

Nutrients were determined by molecular absorption spectrophotometry, following Grasshoff et al. (1999). For the determination of Chl*a*, extraction was carried out in 90% acetone for a period of 10–12h, at −18°C. The spectrophotometric determination was carried out at 665 nm, following Lorenzen (1967) equations. Some equipment (e.g., spectrophotomer) was substituted over the period.

Database

Data collected between 1984 and 2012 in the Ria Formosa lagoon were uploaded into a water quality management database, BarcaWin2000 (see: http://www.barcawin.com). This database includes the results of the various research projects conducted in the Ria Formosa coastal lagoon over the last decades, in a joint effort to enable long term water quality data assessment, including nutrients, oxygen and chlorophyll *a*. Depending on the objective of the past projects, samples were collected at several stations, in various tidal conditions and with different periodicities, especially up until 2006. From this period onward, samples were mostly collected at low water, twice per month until May 2010 and once per month until August 2012. The subsets of data that were analyzed to address each research question are specified in the corresponding result sections. All the data used in this study were obtained from BarcaWin2000 database, except for nitrates by the CIMA laboratory from 2006 (see **Figures 2–5** and **Tables 1–3**).

Statistical analyses

All the statistical analyses were performed using R (R Core Team, 2020). All the variables were standardized and redundant information was filtered through the elimination of linearly correlated variables. A Pearson's correlation test was performed, and when two variables had a correlation coefficient higher than 0.95 only one of them was selected. A principal components analysis (PCA) was performed using the "prcomp" function in R (R Core Team, 2020) to characterize the inter-annual variability of the water chemistry and to analyze which of the analyzed variables were explaining a higher percentage of total variance. ANOVA tests were used to evaluate differences in the mean of single variables

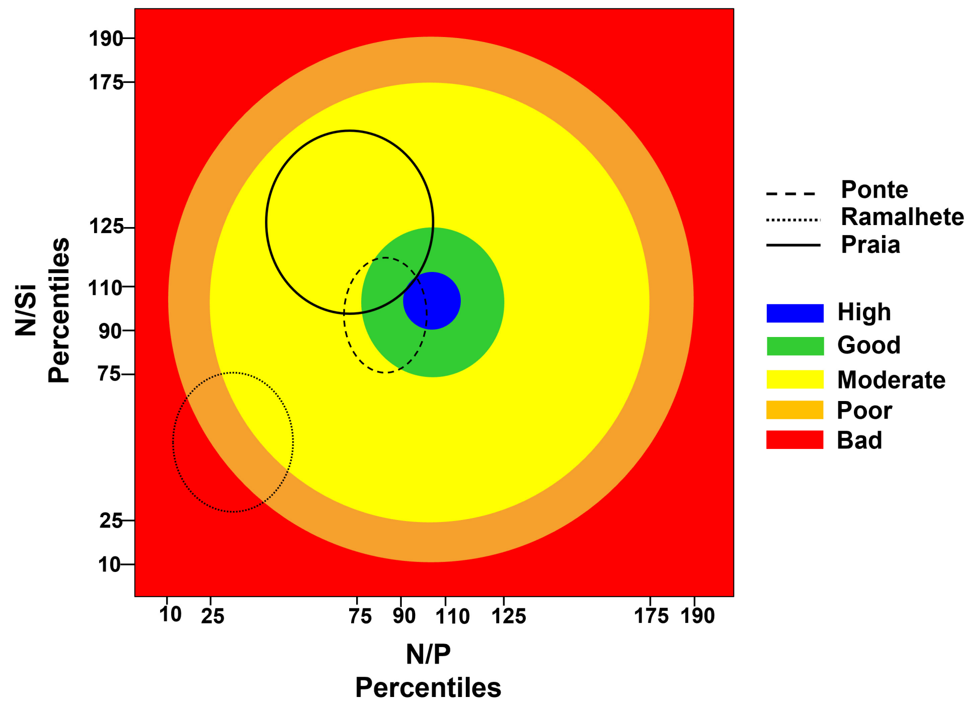

FIGURE 2
N:P and N:Si calculated from the data for the three stations Praia, Ponte and Ramalhete that were used in the boundaries intercalibration exercise for the Water Framework Directive.

(e.g., phosphate). Tukey's pairwise tests were performed to compare differences in the mean of single variables simultaneously with the set of all pairwise comparisons, i.e., groups of sites. PERMANOVA (Anderson, 2001) was used to evaluate differences in the multivariate data set (i.e., distance matrices including all water chemistry variables) between different groups of sites using the "adonis" function in the vegan package (Oksanen et al., 2020) and the "pairwise.adonis" function in the pairwise.adonis package (Arbizu, 2017).

Spatial modeling

The data were aggregated throughout the study period and the mean concentration value was calculated for each parameter and station. An inverse distance weighted (IDW) interpolation was used to map the concentration of each parameter in the study area, as described in Nobre et al. (2005). Concentrations were then reclassified into the five Water Framework Directive classes establishing quality boundaries according to data distribution as follows: High/Good = 0.9 percentile; Good/Moderate = 0.75 percentile; Moderate/Poor = 0.25 percentile; Poor/Bad = 0.1 percentile. In the case of dissolved oxygen, the optimum value is 100% and deviations below that value are considered as signals of deterioration in water quality. However, supersaturation (values much higher than 100%) may also be attributed to eutrophication during daylight hours, with the data split into concentrations below 100% and those above 100%: the percentiles to set quality boundaries were calculated for both data sets. For example, the High/Good boundary was set as the 0.9 percentile of both values below 100% and values above 100%. The same applies for the N:P ratio, which has an optimum value of 16, and the N:Si ratio, which has an optimum value of ~1 (Redfield, 1958; Tett and Lee, 2005).

All data were re-projected using the statistical mapping system ETRS89-LAEA and then analysed using the R software (R Core Team, 2020) together with the gstat package (Pebesma, 2004).

Boundary setting

All the data were used to set the boundaries by calculating the deviations above and below the reference N:P and N:Si ratios (16:1 and 1:1, respectively), separating the data into four sets (N:P $<$ 16; N:P $>$ 16; N:Si $>$ 1; N:Si $<$ 1); the percentiles 0–10,10–25, 25–75, 75–90, 90–100 were used to set the H-High, G-Good, M-Moderate, P-Poor and B-Bad

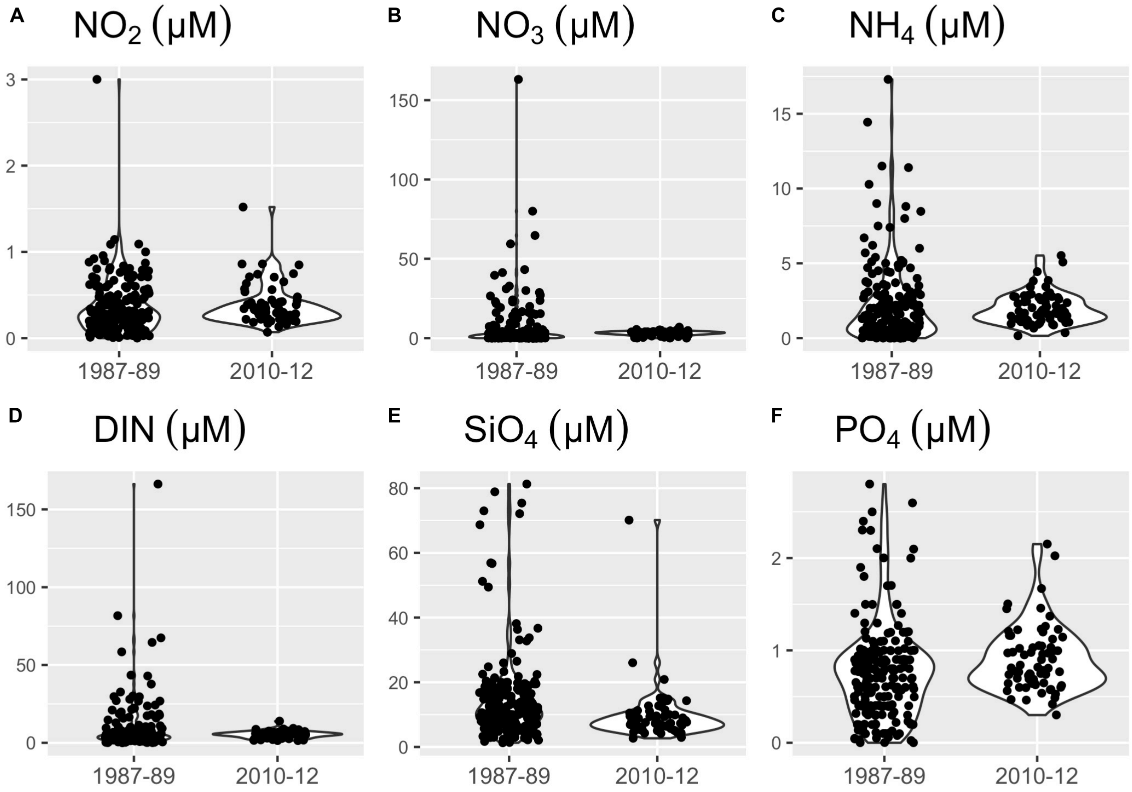

FIGURE 3
Violin plots of nutrient concentrations in micromolar (μM) comparing the two subsets of data: 1987–1989 prior to the interventions, and 2010–2012 after the latest UWWT plant upgrade. **(A)** Nitrite (NO_2); **(B)** Nitrate (NO_3); **(C)** Ammonia (NH_4); **(D)** Dissolved Inorganic Nitrogen (DIN); **(E)** Silicate (SiO_4); **(F)** Orthophosphate (PO_4) from Ramalhete and Ponte in the western lagoon. Raw data are shown as black dots.

boundaries (Table 1). For example, all N:Si values below the 10th percentile of the N:Si < 1 data set and above the 90th of the N:Si > 1 data set corresponded to a bad status for the N:Si ratio. Once the boundaries were set, two of the Ria Formosa stations were used for 'sheltered, coastal waters'. The stations with the longest data sets had been selected as sites for the EU-wide intercalibration exercise (between Member States) that was part of the WFD implementation. Two of the Ria Formosa stations (Ponte and Ramalhete) were used to set the boundaries between High – Good and Good – Moderate conditions. A station outside the lagoon (Praia) was selected for the type specific reference conditions (High). The relevant subset of 948 samples from the database was analyzed.

The mean N:P and N:Si and the mean standard deviation for each group of stations was calculated together with their corresponding percentile, i.e., their position in the percentile ranges calculated earlier using all the data, to assess their nutrient status. Percentile ranges were calculated using the "quantile" function and the correspondence between N:P, N:Si and percentiles calculated using an "empirical cumulative distribution" function.

Results

Question 1: Are the Water Framework Directive intercalibration stations (Ponte and Ramalhete) and the reference station (Praia) significantly different with respect to physico-chemical variables?

A PERMANOVA routine was performed to test the simultaneous response of the variables to the factor Ecological Status of the three stations "Ponte, Ramalhete and Praia," given as: High (H) = Praia; Good (G) = Ponte at Low Water; Moderate (M) = Ramalhete at Low Water. The results of the PERMANOVA show that there are significant differences between the Ecological Status of the 3 stations, ($F = 9.42$; $p = 0.001$). This is consistent with the proposed classifications of High (Praia), Good (Ponte) and Moderate (Ramalhete) status. However, the pairwise comparisons that the differences between categories were significant when comparing High (Praia) with Good (Ponte) and

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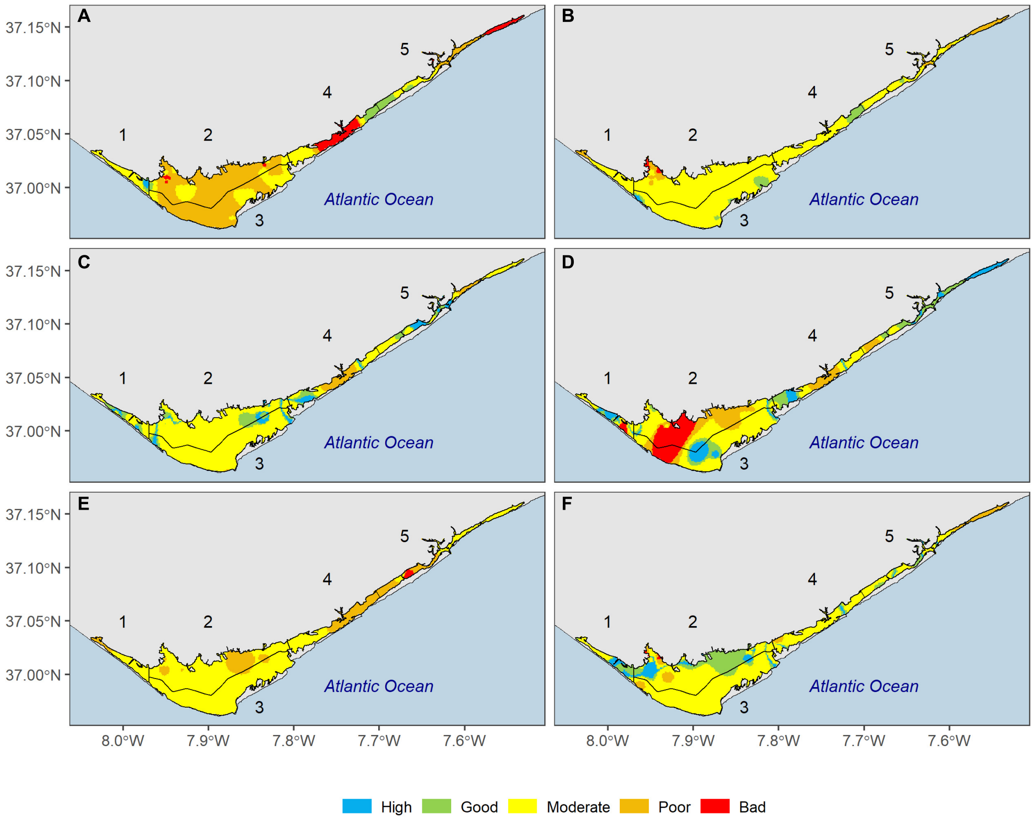

FIGURE 4
Spatial distribution of Ecological Status categories: **(A)** DIN-Dissolved Inorganic Nitrogen (Ammonium, Nitrite and Nitrate); **(B)** DIP-Dissolved Orthophosphate; **(C)** N:P; **(D)** N:Si; **(E)** Chlorophyll *a*; **(F)** Dissolved Oxygen (% saturation). The numbered polygons are the proposed water bodies from Ferreira et al. (2006).

(Moderate) conditions (p-adjusted values = 0.03), but not when comparing Good and Moderate conditions (p-adjusted value = 0.228).

The distribution of the N:P and N:Si data for these stations is shown in **Figure 2** to determine "Nutrient Condition," a a Physico-Chemical Quality Element of the WFD. The size of the circles (line, dashed line, and dotted line) for the 3 stations represents 1 mean absolute deviation from the mean, which lies at the center of the respective circle. The distance of the center of each circle from the (blue) target that represents the reference condition indicates the deviation from the reference condition. This deviation is lowest for Ponte (dashed-line) and highest for Ramalhete (dotted line). The center of the circle for Ponte (dashed-line) lies on the N:Si reference condition axis and is displaced with respect to the N:P reference indicating low N:P ratios. The Ramalhete (dotted line) deviates to the lower left quadrant of the figure, consistent with lower N:P and lower N:Si than the reference condition. The Praia circle (line) deviates to the upper left quadrant, indicating higher N:Si and lower N:P. The circle for Ponte (dashed line) is the smallest, therefore indicating the least variation in the data, whereas the circle for Praia de Faro (line) is the largest indicating the most variation in the data. The results of this analysis are not consistent with the proposed classifications of High (Praia), Good (Ponte) and Moderate (Ramalhete) status.

Question 2: Has the water quality improved in the western section of the Ria Formosa since the 1980's and therefore have the management measures (urban wastewater treatment plants, new inlet, dredging) been effective for reducing nutrients?

The relevant subset of 225 samples for 1987–1989 and 69 samples for 2010-2012 was analyzed to address this question. Stations in the western part of the lagoon with long-term data sets (Ponte and Ramalhete) were considered. The two subsets of data were 1987–1989 prior to the interventions and 2010–2012, after the latest UWWT plant upgrade. The result of the comparison is shown in **Figures 3A–F**. A comparison of the

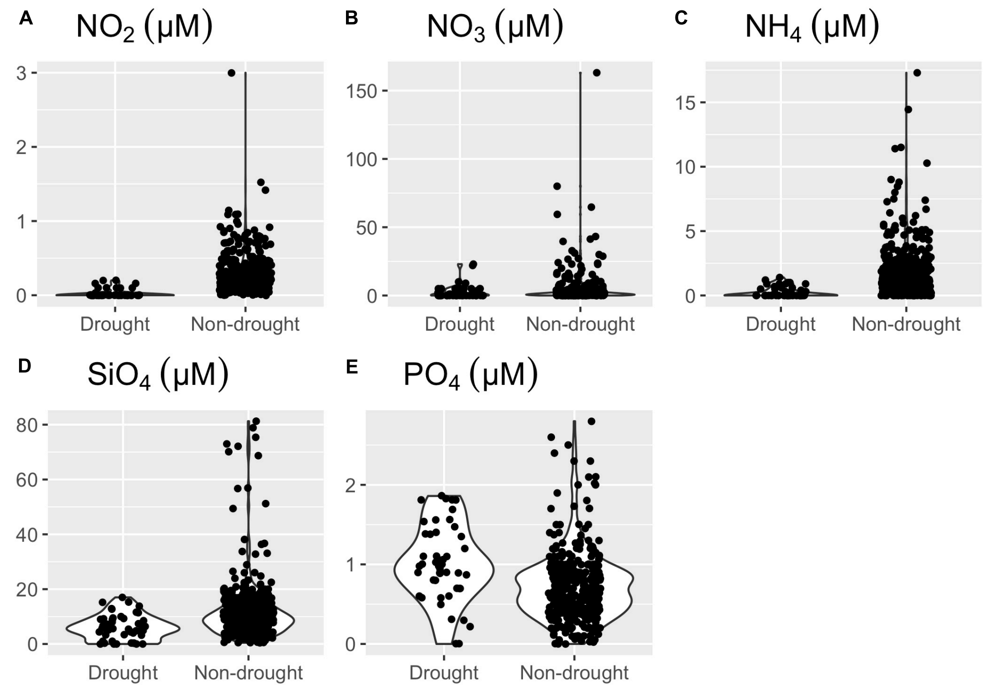

FIGURE 5
Violin plots of nutrient concentrations in micromolar (μM) comparing drought conditions (October 2004 – May 2005) to non-drought conditions (remaining data 1987–2012), showing the median, 95, 75, 25, and 5 percentiles for: **(A)** nitrite (NO_2); **(B)** nitrate (NO_3); **(C)** ammonia (NH_4); **(D)** silicate (SiO_4); and **(E)** orthophosphate (PO_4). Raw data are shown as black dots.

two data subsets shows a decreasing trend for the nutrients monitored, although it was only significant for dissolved inorganic nitrogen ($F = 4.97$, $p = 0.027$) and least for phosphate ($F = 4.28$, $p = 0.039$). Overall, the results show that the combined effect of the management interventions has decreased nutrient pressures to the lagoon, despite increasing resident population and intensification of agriculture in the catchment over the same period.

Question 3: What is the ecological status of the Ria Formosa in the context of the Water Framework Directive, based on the physico-chemical supporting quality elements nutrients and oxygen condition, and the biological quality element phytoplankton biomass using chlorophyll *a* as a proxy?

The results of the boundary setting calculations (High to Bad) are shown in Table 1 and in Figures 4A–F. The maps show the data analysis using the calculated boundary settings, for DIN- Dissolved Inorganic Nitrogen (Figure 4A), DIP-Dissolved Inorganic Phosphate (Figure 4B), N:P (Figure 4C), N:Si (Figure 4D), Chlorophyll *a* (Figure 4E), and Dissolved Oxygen% saturation (Figure 4F).

Figure 4A shows that the concentrations of DIN are elevated throughout the lagoon (moderate to bad), especially elevated in the channel between Olhão and Tavira (bad) and poor in the Faro-Ramalhete area. The phosphate concentrations (Figure 4B) were elevated throughout most of the lagoon (moderate) and the effect of the inlets (good) is clearly seen in green.

Figures 4C,D show the distribution with respect to the stoichiometry of the nutrients (N:P:Si). The colors are based on the Redfield ratio as a reference condition (high), which should be 16:1 for N:P and ∼1:1 for N: Si (Tett and Lee, 2005). Deviation from these ratios (both above and below) are represented by the other colors (good, moderate, poor, bad). The N:P distribution (Figure 4C) shows that the N:P ratio is only close to balanced (green) in the Ancão basin and near Armona. The channel between Olhão and Tavira is poor, consistent with the elevated DIN concentrations. The N:Si distribution (Figure 4D) shows that the N:Si ratio is balanced or close to balanced (green and blue) in the Ancão basin and near the main Faro channel. This most closely represents the water quality of the Ria Formosa. The Ancão and Cacela channel are high, as is the area around the main inlet. The well flushed part of the Faro channel is good, while there are problematic areas around Faro and between Olhão-Tavira.

TABLE 1 Showing the calculated High to Bad boundaries for the Water Framework Directive from all the available data.

	High	Good	Moderate	Poor	Bad
DIN (μM)	x < 0.71	0.71 < x < 1.61	1.61 < x < 7.81	7.81 < x < 16.54	x > 16.54
DIP (μM)	x < 0.11	0.11 < x < 0.25	0.25 < x < 0.93	0.93 < x < 1.44	x > 1.44
N:P ref con = 16	11.85 < x < 17.42	8.26 < x < 11.85; 17.42 < x < 19.87	2.35 < x < 8.26; 19.87 < x < 48.33	0.95 < x < 2.35; 48.33 < x < 98.46	x < 0.95; x > 98.46
N:Si ref con = 1	0.80 < x < 1.12	0.58 < x < 0.80; 1.12 < x < 1.36	0.17 < x < 0.58; 1.36 < x < 3.28	0.08 < x < 0.17; 3.28 < x < 6.36	x < 0.08; x > 6.36
Chl *a*	0.27 > x	0.27 < x < 0.53	0.53 < x < 1.86	1.86 < x < 2.99	x > 2.99
D.0.% sat.	98 < x < 104	94 < x 98; 104 < x < 109	70 < x < 94; 109 < x < 127	45 < x < 70; 127 < x < 140	x < 45; x > 140

The distribution of Chl*a* (**Figure 4E**) is moderate-poor. Higher concentrations were found in the inner parts of the lagoon between Faro and Olhão and in the Marim channel. The percentage saturation of oxygen (**Figure 4F**) is highly variable and mainly moderate. Areas around some of the inlets, although not the Farol inlet, are clearly visible as High-Good. Some of the inner parts of the lagoon have small hotspots that are bad but areas around Faro and Olhao are good and even high.

Question 4: What is the relationship between rainfall, runoff and the nutrient pressures?

The year 2004 was characterized by the lowest rainfall since 1931 (Instituto de Meteorologia [IM], 2004). Thus, the dataset for nutrient concentrations at Ponte from October 2004–May 2005 with a total number of 48 samples was compared to the rest of the data (1987–2012) to determine whether drought conditions were characterized by significantly lower nutrient concentrations (**Figures 5A–E**).

Drought conditions were associated with a significant decrease in silicate ($F = 12.56$; $p = 4.3 \times 10^{-4}$), nitrite ($F = 42.69$; $p = 1.7 \times 10^{-10}$) and ammonium ($F = 30.48$; $p = 5 \times 10^{-8}$) concentrations and a significant increase in phosphate. There was no significant change in nitrate.

Question 5: Are there significant differences in water quality between the lagoon and ocean indicating whether there is an overall export or import of nutrients?

In order to assess this question, data was split into three different groups: Ria Formosa (including the data from all the sampling stations within the lagoon with 2049 samples), inlets (including all the sampling stations at the inlets of the lagoon with a total of 237 samples) and offshore (including all the sampling stations located in the ocean with a total of 315 samples). Then Tukey's test was implemented to assess the differences in nutrient concentrations between all the possible combinations (**Tables 2, 3**).

The nutrient concentrations in the lagoon were always significantly different from the concentrations in the inlets (**Table 2**), being significantly higher in the lagoon (**Table 3**). When comparing the lagoon to the offshore waters, all the nutrient concentrations, except nitrite, were significantly higher in the lagoon. Finally, the inlets and the offshore waters only differed significantly in terms of phosphorus, which was significantly higher offshore. Thus, our results show that the lagoon is generally exporting nutrients into the coastal waters.

Discussion

Monitoring and assessment are necessary for compliance with national and international assessments. Although the WFD has been a major achievement for the protection of European water bodies and their associated biodiversity and ecosystem services, the management and monitoring of some water bodies will most likely require site-specific prediction systems (Hering et al., 2010). This is especially true for highly dynamic (in time and space) ecosystems like the Ria Formosa. The trophic state of the lagoon varies widely in space due to hydro-morphological conditions (e.g., water renewal), but also in time, due to a diversity of factors (e.g., climate). For example, the inner part of the lagoon, where water renewal tends to be low (Mudge et al., 2008), were the most eutrophic. This is in alignment with previous studies showing the importance of water renewal for the eutrophication of coastal lagoons (Tett et al., 2003; Roselli et al., 2013) and the high spatial heterogeneity of these ecosystems (Pérez-Ruzafa et al., 2007). It also supports the findings of Rosa et al. (2022).

Even the water bodies proposed by Ferreira et al. (2006) had heterogeneous chemical conditions, especially in the middle part of the lagoon. There are some mismatches between the

TABLE 2 Tukey's pairwise comparisons of the nutrients' concentrations in three different areas: the inside of the lagoon (Ria Formosa), the inlets that connect it with the sea (inlets) and the offshore waters (Offshore).

	NH_4^+		NO_2^-		NO_3^{2-}		PO_4^{-3}		SiO_4^{2-}	
	Diff	p	Diff	p	Diff	p	Diff	p	Diff	p
Ria Formosa – Inlets	1.31	***	0.07	**	1.64	0.19	0.25	***	7.95	*
Ria Formosa – Offshore	1.93	***	0.06	0.06	2.92	**	−0.15	**	10.6	***
Inlets – Offshore	−0.62	0.89	0.02	0.89	−1.28	0.58	0.40	***	−2.65	0.76

* = $0.01 < p < 0.05$; ** = $0.001 < p < 0.01$; *** = $p < 0.001$.

distribution of the data and the proposed water body boundaries (**Figure 12** in Ferreira et al., 2006). This could lead to the management implications in the context of the WFD and make it very difficult to reach the good ecological status. Thus, long-term chemical and biological data covering wide spatial gradients, including at least those sites with distinct hydro-morphological features, are needed to guarantee the health of dynamic ecosystems, especially in the context of climate change. This is extremely important given the great natural, economic and social capital of this lagoon (Cravo et al., 2022a).

The study defined site-specific water quality based on dissolved oxygen, chlorophyll *a* and nutrient categories according to available long-term data and using percentiles for setting boundaries. According to the results, most of the Ria Formosa is in a moderate state. This is not consistent with our perception of the lagoon, which is heavily influenced by seawater, with high water renewal rates and complex hydrodynamics (Cravo et al., 2013, 2014, 2015, 2022a; Cravo and Jacob, 2019; Verissimo et al., 2019). As an analogy, imagine a small class ($n = 15$) of very able students. If these students are graded using percentage, they may all score over 90%, clearly demonstrating that they are all HIGH scoring and excellent students. However, if they are graded using percentiles with A–E categories, the students achieving 90% or just above will receive an E grade. Thus, it is probable that the boundary setting was inappropriate because of the lack of a strong eutrophication gradient, i.e., most of the studied sites had low chlorophyll *a* and nutrient concentration. The importance of mixing and complex hydrodynamics make the assessment of treated wastewater disposal in the Ria Formosa coastal lagoon particularly challenging (Cravo et al., 2022a). Further studies on site-specific water quality for the Ria Formosa should explore new approaches to redefine the boundaries between water quality categories, e.g., by plotting nutrient data against different pressure variables (Cravo et al., 2015). Nevertheless, the results of this study support the findings of Rosa et al. (2022) of an overall improvement of water quality. The decrease trend in nitrogen concentrations is probably due to a decrease in diffuse pollution coming from agriculture. The surprising small increase trend in phosphate is probably related to lower suspended particles in the water, since phosphate tends to adsorb to particles (Xu et al., 2015), and benthic phosphate release (Murray et al., 2006).

The Ria Formosa is an important area for the culture of bivalves and these filter feeders rely on plankton productivity. In addition, it is important as a nursery for juvenile fish. Thus, the nutrient condition is important not only for compliance with the WFD but also for the dynamics of phytoplankton communities in the lagoon (Brito et al., 2012a), while chlorophyll *a* and dissolved oxygen are important for the bivalves and other consumers. Understanding the link between hydrodynamics, water quality and the delivery of valuable ecosystem services is key to this management approach (Newton et al., 2018; Pérez-Ruzafa et al., 2019; Cravo et al., 2022a).

A system approach to the management of the Ria Formosa, is necessary to preserve this valuable social-ecological system (Newton, 2012; Gari et al., 2014). Several environmental management measures have been implemented over three decades to improve the water quality of the western part of the lagoon. These include the installation (1989) and subsequent upgrade (2009) of UWWT plants, dredging (June 1997) and relocation of Ancão inlet. The investment in such high-cost infrastructure has probably contributed to the improvement in the water quality that is indicated by our data analysis.

TABLE 3 Mean values and standard deviation of nutrient concentrations in n three different areas: the inside of the lagoon (Ria Formosa), the inlets that connect it with the sea (Inlets) and the offshore waters (Offshore).

	NH_4^+		NO_2^-		NO_3^{2-}		PO_4^{-3}		SiO_4^{2-}	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ria Formosa	2.50	3.55	0.29	0.37	5.33	14.45	0.74	0.67	13.40	47.21
Inlets	1.18	1.26	0.22	0.36	3.69	6.36	0.48	0.44	5.44	8.88
Offshore	0.56	0.55	0.23	0.30	2.40	2.13	0.89	1.40	2.79	3.62

Nevertheless, based on all the available data and on the "one out all out principle", most of the Ria is classified as "moderate" and less flushed areas around Faro, Olhão and the Olhão-Tavira channels show up as "poor" or "bad" nearest to Tavira. Again, this result is surprising, and probably an artifact of applying an inappropriate boundary setting.

Management measures such as damming, dredging and inlet modifications can alter the physiography and hydrology of coastal lagoons (Roselli et al., 2013) thereby also modifying their functioning, such as residence time and flushing. The opening of an artificial inlet (Dias et al., 2009) and its subsequent closure may have modified aspects of the lagoon dynamics and the water bodies.

Furthermore, lagoons are sentinel systems for climate change (Eisenreich, 2005), so the response of the lagoon to climate change (Brito et al., 2012b; Rodrigues et al., 2021) and climate variability (drought-wet years) is important. This knowledge is necessary to understand how climate change will influence important fish and shellfish resources in the Ria Formosa and the economic activities depending on them (Newton et al., 2018; Pérez-Ruzafa et al., 2019). Management can use this knowledge to develop tools and strategies that help fisheries, aquaculture sectors and local authorities to prepare for the adverse changes or future benefits of climate change (e.g., CERES[2]). Changes in the productivity and ecology of the lagoon would have important economic consequences for these aquatic industries and knowledge is necessary to assess exposure, vulnerability and adaptive capacity within the fisheries and aquaculture sectors in order to suggest viable solutions for aquatic food production industries. These economic sectors will have to handle risks and expected benefits from climate change. In particular, it may be possible to support the ecological intensification of aquaculture in the lagoon, with the dual objectives of increasing production and competitiveness of the industry, while ensuring sustainability and compliance with EU regulations on food safety and environment. However, eco-intensification of aquaculture is a transdisciplinary challenge that requires the integration of scientific and technical innovations, new policies and economic instruments, as well as the mitigation of social constraints (e.g., GAIN[3]).

Conclusion

This study assessed the effectiveness of management measures in the Ria Formosa by answering 5 research questions that are important for the adaptive management of this valuable coastal lagoon for Blue Growth in the context of climate change:

1. The WFD intercalibration stations (Ponte and Ramalhete) and the reference station (Praia) are significantly different with respect to physico-chemical variables. This environmental variability is typical of complex systems such as lagoons (Pérez-Ruzafa et al., 2019). This may be attributed to the classification of the Ria Formosa as a "sheltered coastal water" rather than a "transitional" water. Although the Ria Formosa does not have the salinity gradient required to be classified as a transitional water under the WFD, nevertheless it is a region of restricted exchange that is behaves more as a transitional than coastal water (Tett et al., 2003; Newton and Icely, 2006; Zaldívar et al., 2008).
2. The water quality in the western section of the Ria Formosa has improved, indicating that the management measures have been partially effective, with respect to nutrients and oxygen saturation. However, there have been parallel studies, with shorter time series, of microbial contamination, metals and pesticides that are also relevant to water quality (Bebianno et al., 2019; Moreira da Silva et al., 2019). Microbiological contamination is still a concern (Cravo et al., 2015, 2022a; Galvão et al., 2019) is further evidence of metal, pesticide and pharmaceutical contamination and pollution (Silva et al., 2021; Cravo et al., 2022b).
3. The Ecological Status of the Ria Formosa in the context of the WFD is very spatially variable, based both on the physico- chemical supporting quality elements nutrients and oxygen condition and the biological quality element phytoplankton biomass with chlorophyll *a* as a proxy. The assessment results, following the "one out, all out" principle classify most of the water as "moderate" indicating that further management measures may be necessary. However, we believe this maybe a consequence of boundary setting forcing 5 categories in a system that has excellent tidal flushing with high-good quality coastal water.
4. The spatial distribution of the data is not consistent with the WFD water bodies derived from Ferreira et al. (2006) methodology. This may be due to changes in spatial complexity, particularly, in the western part of the lagoon, where inlets have been relocated (Pérez-Ruzafa et al., 2019).
5. Rainfall and runoff significantly affect the nutrient pressures in the Ria Formosa lagoon so that there are significant decreases in nutrient pressure in drought years. Results from winter 2021–2022, that was a particularly severe drought are not yet available, but it is probable that nutrient pressure also decreased due to decreased runoff. This is relevant in the context of climate change, whether rainfall increases or decreases. Increased temperatures will significantly affect oxygen solubility and the probability of hypoxia will increase (Brito et al., 2012a).

2 www.ceresproject.eu
3 https://cordis.europa.eu/project/rcn/216474/factsheet/en

6. There are significant differences in water quality between the lagoon and ocean indicating that the lagoon both exports and imports nutrients at different times of the year (Newton and Mudge, 2005; Cravo et al., 2013, 2014, 2015; Cravo and Jacob, 2019; Rosa et al., 2019).
7. Ocean-color is increasingly used for chlorophyll *a* estimations. Indeed, some of the data sets included in the study were obtained for sea-truthing of ESA missions. There are also new opportunities for monitoring using new remote sensing products from ESA's Sentinel missions (Cristina et al., 2019; El Mahrad et al., 2020). However, the reliability of ocean-color products depends on sea-truthing. Establishing long-term baselines, especially for climate change studies.
8. Despite the considerable efforts with respect to the installation of sewers and sewage treatment, there are still reports of sewage contamination in urban areas such as Faro and Olhao affecting the water quality. This has been investigated using robotic cameras and is mainly due to 'illegal' linking of sewage to rainwater-drains, in some cases a long time ago and prior to records.
9. The baseline for Ecological Status assessments of the WFD are type-specific reference conditions. These are most useful to assess whether the management measures are resulting in improvements in the water quality and ecological status of a system. They are less useful to make comparisons with other systems within the country or other EU Member States even from the same eco-region because of differing protocols. Intercalibration is therefore especially important in trans-boundary waters. For example, it would not be coherent for a shared water body to be classed as 'moderate' on one side of an international border and 'high' on the other side. Using the same agreed methods for assessment is also important since, different assessment methods applied to the same data set can give very different results (Newton et al., 2003).

Finally, management measures have had a positive effect on the water quality of the lagoon. The management of the water quality and ecological status are now legally binding and non-compliance is subject to fines from the European Union under the WFD. The 2019 EU "*fitness Check*" of the cluster of Water Directives concluded that they are "*overall fit for purpose, with some room for enhanced effectiveness*". The main shortcomings were attributed to insufficient implementation by Member States and Economic Sectors, such as agriculture. The findings of the present study indicate that some adjustments to the implementation may be necessary (conclusions 1, 3, 4, 8, 9). The EU "*fitness check*" also concluded that the WFD was "*future-proof*" and sufficiently flexible to accommodate new threats (e.g., pharmaceuticals, microplastics and climate change). The findings of the current study do support that there has been an overall improvement, but this may not continue with climate change, especially if temperatures increase (conclusion 5). Nonetheless, the continued threat from chemicals recognized in the EU "*fitness check*" is also true in the case of the Ria Formosa (Conclusion 2).

Data availability statement

The datasets generated for this study are available on request to the corresponding author.

Author contributions

AN: integrated her expertise on chemical oceanography and eutrophication and the implementation of the Water Framework Directive to contribute to all aspects of the article. MC-A: statistical analysis of the data and production of **Figures 2–5**, and writing and editing. DM: statistical analysis and production of the maps in **Figures 1**, **4**. PG: data collection and analysis, database management, and writing and editing. SC: data collection and analysis, database management, and draft writing and editing. MZ: data collection and analysis. JI: data collection, writing, editing, and preparation of the article for final submission. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author JI was a senior researcher with the research centre CIMA, at the University of Algarve, Portugal; he is also the co-owner of the Portuguese company Sagremarisco-Viveiros de Marisco Lda.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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