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Lagoon-sea exchanges, nutrient dynamics and water quality management of the Ria Formosa (Portugal)

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Abstract

Historical data from the Ria Formosa lagoon are classified according to the EEA 2001 guidelines to provide a frame of reference to evaluate the effect of management during the implementation of the environmental legislative Directives. Water samples from the Ria Formosa lagoon were significantly enriched in nitrogen (NH_4^+ NO_2^- and NO_3^-) with respect to the adjacent coastal waters indicating that inputs from sewage, agricultural runoff and benthic fluxes were not fully assimilated within the lagoon. Tidal flushing was insufficient in the inner areas of the lagoon to remove or effectively dilute these inputs. Enrichment was most severe close to the urban centres of Faro and Olhão, as well as in the Gilão Estuary and the shallow extremities. Dissolved oxygen undersaturation (mean 75% during daylight hours) was associated with the area close to the sewage outlets of Faro. In the shallow west end of the lagoon during summer, dissolved oxygen supersaturation reached 140% during the day but fell to 50% at night. Classification using the EEA (2001) guidelines suggests the system is "poor" or "bad" with respect to phosphate concentrations for the majority of the year and "poor" in nitrogen contamination during the autumn rainy period. Due to the high overall nitrogen load in the lagoon, there is a net export to the coastal waters, especially during November and December, and phosphate only becomes limiting briefly during the spring bloom (April). Therefore, substantial phytoplankton populations may be supported year-round in the lagoon. The consequences of water quality deterioration in the Ria Formosa would negatively affect the lagoon as a regional resource, important for its ecological, economic and recreational value. The industries most affected would be tourism, fisheries and aquaculture. Management options include Urban Waste Water Treatment, dredging, artificial inlets, limits on urban development and changes in agricultural practices.

Keywords: nutrients; coastal lagoon; Eutrophication Ria Formosa

1. Introduction

New interpretations of existing data are useful tools in reconstruction of scenarios and for the development of management strategies (Jackson, 2001). A review of historical data of the Ria Formosa is deemed necessary to provide the "before management" frame of reference and to assess the possible management options during the implementation of environmental legislative Directives. Dissolved nitrogen and phosphorus are assimilated by both algae (phytoplankton, microphytobenthos and macrophytes) and bacteria (autotrophic and heterotrophic, Webb, 1981). The Redfield ratio (C:N:P 106:16:1) summarises the composition of marine organisms and is often used to describe the cycling and limitations of nutrients in seawater (Geider and La Roche, 2002). Nitrogen is usually the limiting nutrient in temperate lagoons (Krumbein, 1981) although some are rarely phosphorus limited (Mee, 1978; Nowicki and Nixon, 1985). Silicon is an additional nutrient required

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by diatoms although the silica geochemical cycle has a much smaller biologically mediated component compared to the other nutrients. Mineralisation is mainly a chemical solution process (Webb, 1981) either by dissolution of diatom frustules or from the diagenesis of aluminosilicate clays (Pomeroy and Imberger, 1981). In lagoons with large plant biomasses or organic contamination, the measurement of dissolved oxygen provides an easy measure of water quality. Systems can alternate between supersaturated conditions during daylight hours due to photosynthesis and undersaturated at night due to respiration.

The Ria Formosa is a large coastal lagoon in southern Portugal (Fig. 1). The main physical characteristics of the lagoon including the temperature and salinity distribution have been described elsewhere (Newton, 1995; Bebianno, 1995; Newton and Mudge, 2003). Many of the economically important activities of the surrounding area are directly or indirectly related to the lagoon. The most evident are tourism, abiotic resource exploitation such as salt and sediment extraction and the biotic resource exploitation, including bivalve aquaculture and fisheries. Many fish species are taken within the lagoon, and the Ria Formosa is an important nursery for species caught in the surrounding coastal waters.

Several articles have covered aspects of the water quality of Ria Formosa lagoon: Bebianno (1995; contamination by metals); Mudge and Bebianno (1997); Mudge et al. (1999) (sewage contamination); Baptista (1993; microbial contamination) and Sampayo et al. (1990; nuisance blooms) although little information is available regarding the biologically important nutrients. As part of a larger study of this lagoon, the present paper presents information on the nutrient status and the dissolved oxygen concentrations in the Ria Formosa.

Potential sources of nutrients to the Ria Formosa include the Atlantic Ocean waters, sewage, agricultural runoff and benthic fluxes (Newton, 1995; Newton et al., 2003). The Campina de Faro is the most intensively farmed area of the Algarve, and corresponds to the drainage basin of the Ria Formosa. Rapid urbanisation of this fertile area has been partially controlled by creating zones reserved for agriculture. The Atlantic Ocean waters flowing into the Ria Formosa provide a limited quantity of nutrients to the lagoon (Falcão and Vale, 2003). However, nutrient supply within the lagoon is supplemented by the poorly treated domestic sewage inputs from a population of more than 100,000 inhabitants. This represents approximately 400 Metric tons of nitrogen per year and 200 Metric tons of phosphorus per year from domestic sewage and detergent, (World Bank, 1993). The population increases considerably in the summer months due to tourism. Domestic sewage is an important source of ammonium and phosphate particularly near the towns of Faro and Olhão (Newton, 1995). Previous studies of the lipid biomarkers have shown enhanced sewage indicators in several areas, principally in the inner lagoon (Mudge et al., 1999). The fatty acid biomarkers for algal production highlighted some outer lagoon and inlet sites as having high diatom biomass whereas the inner regions had a more diverse community (Mudge et al., 1998). More recently, much of the sewage disposal into the western lagoon has been concentrated around the Ramalhete channel near the airport.

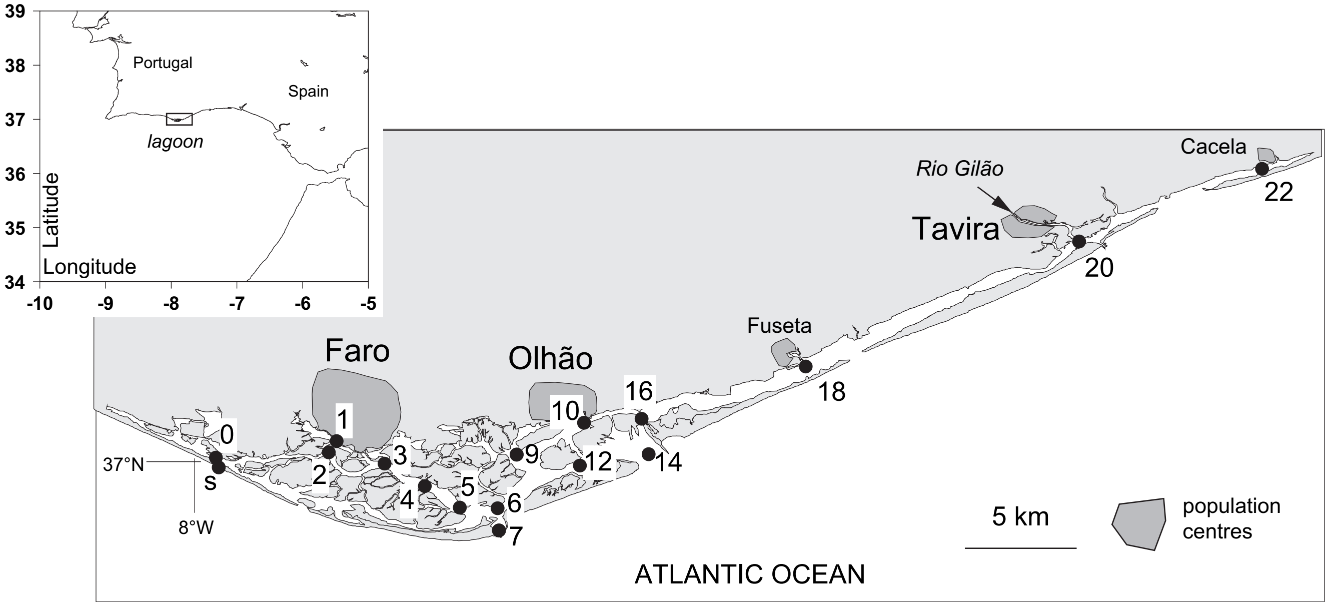

Fig. 1. The Ria Formosa lagoon showing the location of the sampling stations relevant to the nutrients and oxygen measurements.

The hinterland of the lagoon is farmed intensively with the use of ammonium nitrate, urea and phosphate fertilisers. Rainfall, and resulting agricultural runoff, is seasonal with particularly high inputs associated with the autumn rains (Newton et al., 2003), further inputs during the rainy months and another pulse in spring when rainfall occurs after the springtime fertiliser application (Newton, 1995). In shallow areas of the lagoon, where a small volume of water is in contact with a large surface area of sediment, benthic fluxes are another important source of nutrients (Falcão and Vale, 1990a,b).

2. Materials and methods

The temperature and salinity regimes (Newton and Mudge, 2003) divide the lagoon into three distinct zones:

- the inner lagoon at sites 0–3, 9–10, 18, 20 and 22 in Fig. 1;
- the outer lagoon at sites 4–6, 12 and 16;
- the inlets at sites 7 and 14.

Seawater was collected from outside the lagoon from Faro Beach indicated as site S on Fig. 1. Water samples were collected in pre-cleaned plastic bottles at all sites monthly for a 12 month period from June 1987 to May 1988 and analysed for ammonium, nitrite, nitrate, phosphate and silicate according to the methods of Grasshoff et al. (1983). Dissolved oxygen was derived from modified Winkler titrations (Grasshoff et al., 1983) after on site fixation. Sampling dates coincided with neap tides when tidal flushing was minimal. The effects of tidal flushing were assessed by sampling at both high water (noon) and low water (early morning). An inner lagoon station (0) was selected for a subsequent annual survey (January to December 1989) and compared to the adjacent coastal water (S). Sampling coincided with low water springs and neaps for the inner lagoon in order to characterize the residual water within the lagoon. The coastal seawater was sampled (S) at high water in order to minimize the risk of contamination from out-flowing lagoon water.

3. Results

The mean concentrations at each sampling station for each nutrient are presented in Figs. 2 and 3 (nitrogen species) and Fig. 4 (phosphate and silicate). In each case, the bars represent the mean of 12 monthly observations at low water neaps taken during daylight hours.

Highest concentrations of ammonium (Fig. 2a) were measured near sewage outlets in the inner lagoon (stations 0–2 and 10) and at sites 18 (Fuzeta), 20 (Gilão Estuary, Tavira) and 22 (Cacela). Significantly ($P \sim 0.02$ for t-test of paired data) lower concentrations could be seen in the surface waters at the inlets. The main inlet at station 7 had the lowest annual mean ammonium concentration. The monthly variation in the concentration at station 7, representing inflowing Atlantic Ocean coastal waters and station 1, a shallow, inner lagoon site close to a sewage outlet is shown in Fig. 3a. Enhancement in the ammonium concentration at the inner lagoon site can be seen at most times during the year, especially over the winter months when rainfall is greatest.

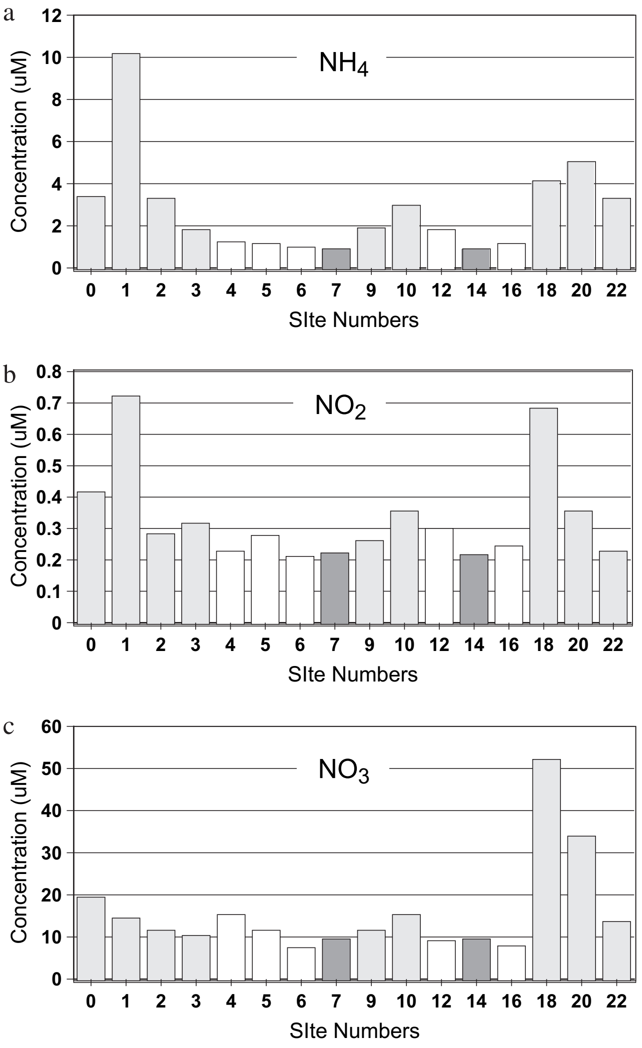

Fig. 2. Aqueous (a) ammonium; (b) nitrite; and (c) nitrate concentrations in the Ria Formosa at low water neaps. The bars represent the 12 month mean. The inlets are darkly shaded, the outer lagoonal sites are unshaded and the inner lagoon sites are lightly shaded.

A similar distribution can be seen with nitrite although the enrichment at the most easterly sites (18–22) was not as strong as that seen at the more westerly sites (Fig. 2b). Concentrations are low (0.2–0.3 μM) in the outer lagoon sites and the inlets. Nitrite concentrations

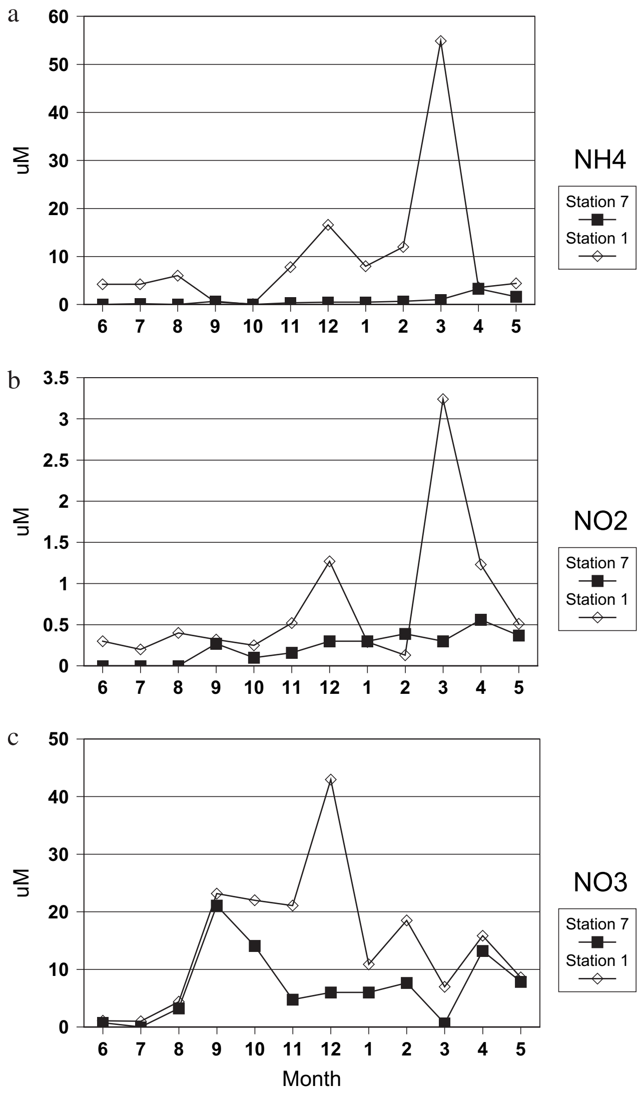

Fig. 3. A comparison of the monthly concentrations of ammonium (a); nitrite (b); and nitrate (c) at sites 1 and 7.

in the lagoon were usually twice those of the Atlantic Ocean coastal water. The monthly variation of nitrite (Fig. 3b) was almost identical to that of the ammonium. However, the magnitude of the enhancement over the winter months was not as great as for the ammonium-N.

There appears to be little immediate effect of the increased lagoon ammonium or nitrite concentrations on the inflowing Atlantic seawater. However, in both cases, slightly elevated concentrations can be seen in the month following the spring peaks (April). These increases cannot be accounted for by the lagoon alone and so probably represent increased terrestrial runoff for the whole coastal region.

Elevated mean annual nitrate concentrations (Fig. 2c) compared to the inlet concentrations were found at Fuzeta (18) and the Gilão Estuary at Tavira (20), and also to a much lesser extent at the shallow stations near the ends of the west (0) and east channels (22). Nitrate can be supplied by inflowing Atlantic water, remineralization (Brockel, 1990; Falcão and Vale, 1990a; Newton, 1995; Newton et al., 2003), agricultural runoff in winter and sewage (Newton, 1995; Newton et al., 2003).

The monthly variation in nitrate-N (Fig. 3c) was different to those of ammonium and nitrite. The Atlantic Ocean coastal water (station 7) co-varies with the inner lagoon waters (station 1) during summer and early autumn; maximal enrichment in the lagoon was seen during December, coincident with an increase of the other forms of nitrogen. The most notable difference was the lack of any increase during spring. In general, the enhancement of the inner lagoon nitrate concentrations throughout the year is not as great as with the other more reduced forms of nitrogen.

High concentrations of phosphate (Fig. 4a) were associated with the shallow station near the east end of the lagoon (22), the towns of Faro (1, 2), Olhão (9, 10) and Fuzeta (18) and the Gilão Estuary at Tavira (20) Sources of phosphate include the Atlantic Ocean (coastal waters represented by station 7) and supplemented by remineralization, inputs from sewage and agricultural runoff (Newton, 1995; Newton et al., 2003). In the Ria Formosa, the increased phosphate concentrations seen in the inner lagoon, were consistent with the position of the sewage discharge, as well as shallow stations where remineralization is important. In the

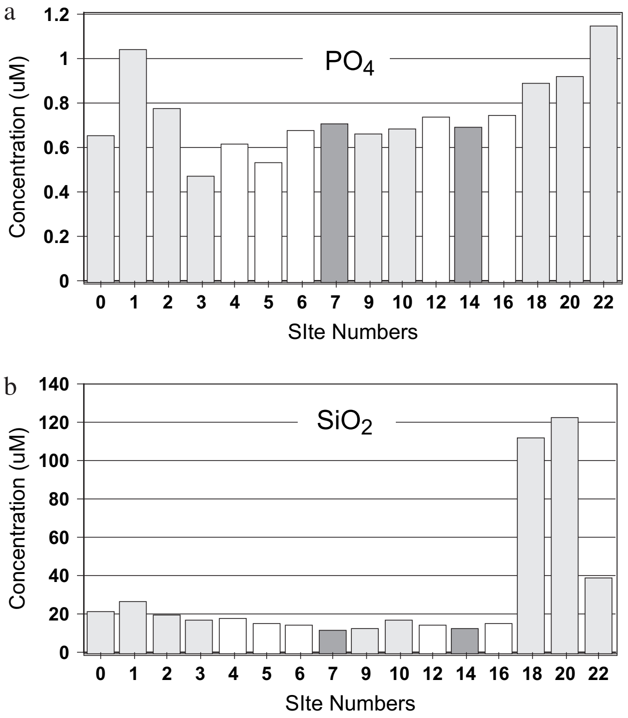

Fig. 4. Aqueous (a) phosphate; and (b) silicate concentrations in the Ria Formosa at low water neaps. The bars represent the 12 month mean. The inlets are darkly shaded, the outer lagoonal sites are unshaded and the inner lagoon sites are lightly shaded.

outer lagoonal sites, lower concentrations compared to either the inner sites or inflowing Atlantic waters were observed. This was probably due to use of this nutrient by the biota.

High concentrations of silicate (Fig. 4b) were found near Fuzeta (18) and the Gilão Estuary at Tavira (20) as well as a shallow station near the east end of the lagoon (22). The increased means observed at stations 18 and 20 are consistent with freshwater runoff and not sewage. In this respect, silicate can be considered as a "clean nutrient".

The annual mean dissolved oxygen percentage saturation observed at the sampling stations is shown as a box and whisker plot in Fig. 5. Although all the measurements were taken during daylight hours, the mean of 12 months' data taken at high water neaps is 75% at station 1 near the town of Faro. This compares to 90% at low water. Persistent undersaturation at this station was attributed to organic loading from Faro sewage. A smaller decrease in the percentage saturation can also be seen at station 10 near the Olhão sewage discharge point. In contrast, the high water mean dissolved oxygen percentage saturation at station 0, the shallow station near the west end of the lagoon, was closer to 100% but with a substantial number of samples greater than this. The supersaturation associated with this station during daylight hours was attributed to the phytoplanktonic and phytobenthic primary production promoted by high nutrient availability. Similar observations by Durham (2000) and Newton and Icely (2002) indicate the oxygen maximum is entirely dependent on the time relative to noon and independent of the tide. The night-time decrease in oxygen in summer reached minima of less than 50% saturated at Faro.

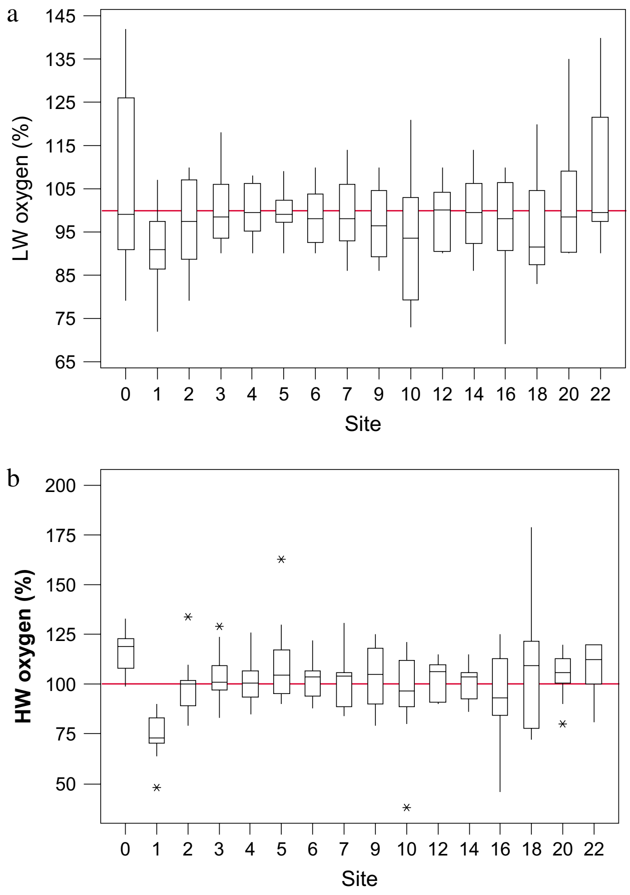

Fig. 5. Box and Whisker plot of the oxygen saturation measured at (a) LW; and (b) HW. A line is drawn across the box at the median. The bottom of each box is at the first quartile (Q1), and the top is at the third quartile (Q3) value. The whiskers are the lines that extend from the top and bottom of the box to the adjacent values. The adjacent values are the lowest and highest observations that are still inside the region defined by the following limits: Lower Limit: Q1−1.5 (Q3−Q1). Upper Limit: Q3+1.5 (Q3−Q1). Outliers are points outside of the lower and upper limits and are plotted with asterisks (*).

4. Discussion

In general, all nutrients were enriched at stations in the inner lagoon with respect to the inflowing seawater. Enrichment was particularly high at stations 1 and 10, near the towns of Faro and Olhão, as well as 18, 20 and 22 near Fuzeta, Tavira and Cacela, respectively. The elevated concentrations at these stations were observed irrespective of the state of the tide indicating that the inner areas of the lagoon are not completely flushed by the tidal exchange, confirming the observations made by Newton and Mudge (2003).

The import and export of N to the Ria Formosa through the main channel at station 7 (Fig. 6) was assessed by quantifying the differences between high water (inflowing seawater) and low water (outflowing lagoonal waters). The major N form in all exports and imports was nitrate despite comparable concentrations of ammonium in the waters (cf. Fig. 3).

There was a net import of N during autumn and spring probably due to biological usage of N by phytoplankton and bacteria in the lagoon leading to depletion in the outflowing waters. Increased nitrate in lagoonal waters over late autumn and winter may be

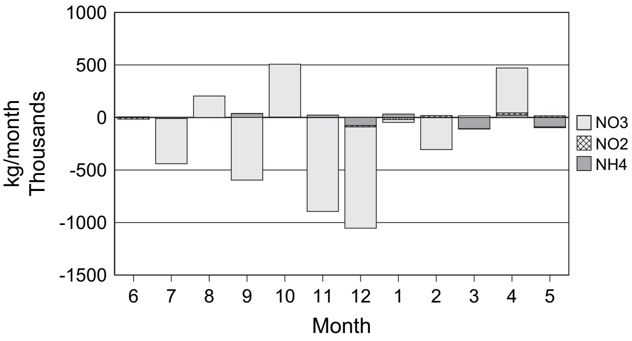

Fig. 6. The nitrogen budget through station 7, the main inlet. Negative values represent an export of nitrogen from the system.

due to: (a) microbial regeneration of either marine or terrestrial organic compounds; and/or (b) the terrestrial runoff of fertilisers. These dates coincided with maximum rainfall and river flow (Newton et al., 2003). The net result, however, was an export of nitrogen through station 7 (~2000 tonnes annually). Almost 60% of total annual export occurs during the two winter months of November and December.

Despite these exports, the Ria Formosa is still enriched with nitrogen relative to the Atlantic coastal waters. Inner lagoon sources include nutrient remineralization at the sediment interface, particularly in shallow areas (Falcão and Vale, 1995, 1998; Newton et al., 2003). Nitrogen enrichment of the inner lagoon is also associated both with urban centres and agricultural areas. The effect of agricultural runoff is particularly marked in the wet winter months. In all cases, the nutrient concentration was greater in the winter months than during the summer although there was enrichment with respect to the Atlantic seawater (e.g. site 7) throughout the year.

The majority of agricultural fertilisers contain nitrogen in the forms of ammonium and nitrate, often as ammonium nitrate (NH_4NO_3), but increasingly other forms such as urea have been applied (Cresser et al., 1993). Nitrogen in soil that is available for uptake can be present as ammonium or as nitrate following conversion by soil microbes (Addiscott, 1996). Nitrite is less stable than the other two forms and is usually only present in small concentrations. Nitrate is completely soluble in water and is vulnerable to wash out through percolating rainfall or irrigation (Addiscott, 1996). Nitrogen containing fertiliser is usually applied at the beginning of the growing period but to assess the overall contribution to surface waters, Addiscott (1996) recommends that the entire year be assessed especially since different forms of nitrogen may be important at different times of the year.

The oxidised/reduced nitrogen ratio (NO_2+NO_3/NH_4) remains reasonably constant throughout most of the year (2.4 ± 1.2 one SD) although in late autumn and winter, the ratio jumps to values up to 20. The oxidation and reduction transformation processes in the nitrogen cycle are controlled by the availability of oxygen and hence whether sediments are oxic or anoxic (Rheinheimer, 1985). However, in this case the increase in ratio is coincident with an increase in overall nitrogen concentration highlighting its speciation as nitrate rather than ammonium.

The mean annual ratio between the dissolved inorganic N species and phosphate (N/P) can be seen in Fig. 7. The Redfield ratio for N and P (16) is exceeded in each case implying there is an excess of nitrogen relative to phosphorus. There are spatial trends within the data with highest ratios measured in water samples from the inner lagoon sites. In the same figure, the mean annual ratio between the dissolved inorganic N species and silicon is presented with a key threshold value of 1. At all sites, the ratio is 1.0 or greater and it is substantially greater in the outer lagoon sites implying a great excess of nitrogen relative to the silicon. Silicon is required by diatoms and is actively scavenged from the water. Previous analyses of fatty acids (Mudge et al., 1998) has identified the outer lagoon sites as having biomarker signatures specifically for diatoms while a mixed phytoplankton signature exists in the inner site sediments.

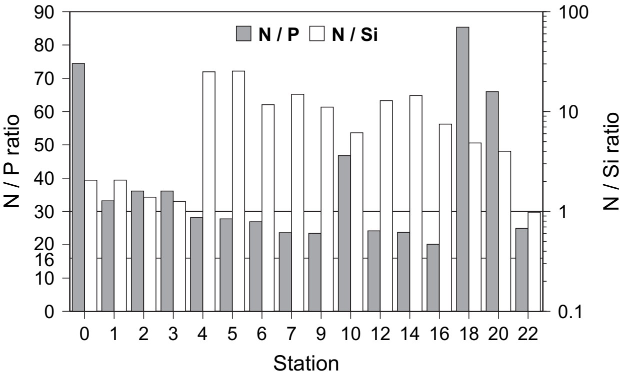

Fig. 7. The mean annual N/P and N/Si ratios for each of the stations in the Ria Formosa. Values of key ratios (16 for N/P and 1 for N/Si) are shown by horizontal lines.

The temporal variation of the N/P and N/Si ratios at site 0 (inner lagoon) in the following year can be seen in Fig. 8a. The data were significantly lower than those measured in the previous year and, in general, the ratios were less than the Redfield ratios until the autumn period. In both cases, neither phosphorus nor silicon were limiting during the bloom period in spring. A similar trend can be seen in Fig. 8b with seawater collected from outside the lagoon (site S on Fig. 1). In spring (~day 120), the N/P ratio increased dramatically indicating a depletion of P relative to N. This can be seen to a lesser extent in the inner lagoon site (Fig. 8a) and probably corresponds to the time of the spring bloom. The short duration of this effect implies a relatively rapid resupply of phosphate to the system.

A plot of the N/P ratio in relation to the total dissolved inorganic nitrogen concentration can be seen in Fig. 9a. The figure is divided into regions according to the water quality classification for coastal waters from the EEA (2001). When the N/P ratio exceeds 16 at the end of the year, the total N concentration is also high implying an input of nitrogen to the system probably associated with rainfall. At other times of the year, although the N/P ratio exceeds 16, it is not accompanied by an increase in total N implying a depletion of P instead. The same data can be plotted against the phosphate concentration in the waters (Fig. 9b). This shows that the phosphate concentrations are relatively high with many dates (shown as day numbers) falling in

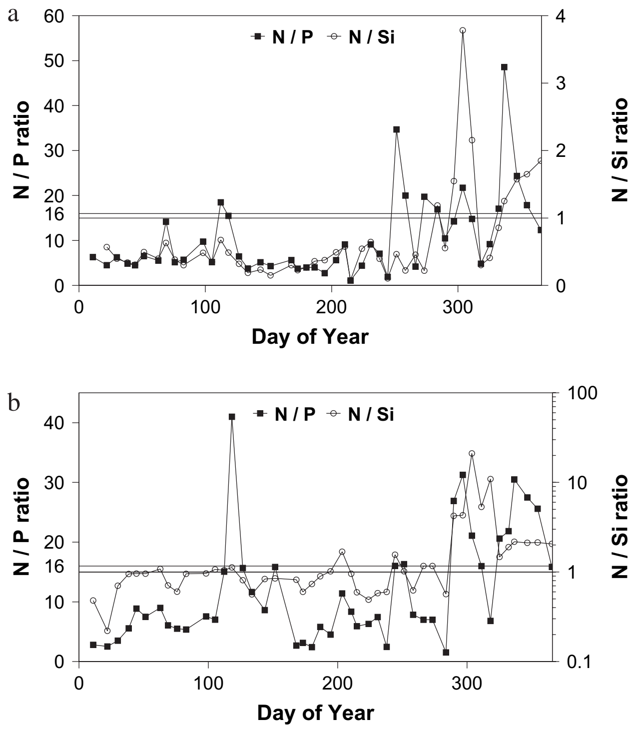

Fig. 8. The temporal variation in the N/P and N/Si ratios from (a) site 0 in the inner lagoon; and (b) site S, the seawater outside the lagoon. Note the horizontal lines for the key ratios.

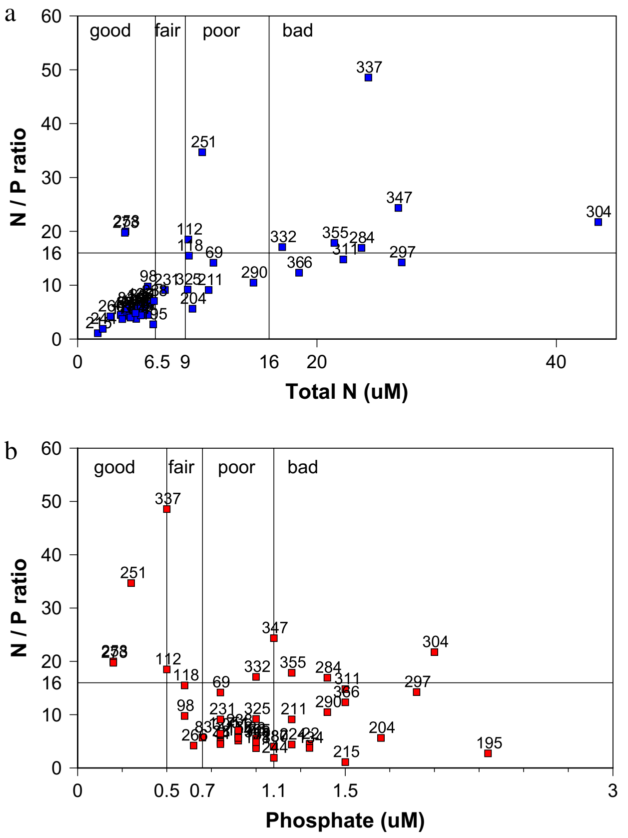

Fig. 9. The N/P ratio at site 0 in the inner lagoon plotted against (a) the total nitrogen concentration; and (b) the phosphate concentration. In each case, key values by which the water quality can be classified according to the EEA (2001) are included. Note the horizontal line for the key ratio.

the “poor” or “bad” categories (EEA, 2001). The “bad” samples are principally during the summer and autumn months. In several cases, although the phosphate concentration is relatively high, the N/P ratio is greater than 16 implying the enrichment with nitrogen is even greater. Nevertheless, using the U.S.A. National Estuarine Eutrophication Assessment index, (Bricker et al., 1999) the Ria Formosa is only impacted in the inner channels (Newton et al., 2003). When the Ria Formosa is compared to other European coastal systems with restricted exchange ranging from bays to fjords (Tett et al., 2003), the system is seen to be robust and has a low susceptibility to eutrophication pressures.

The main source of silicate in the Ria Formosa appears to be a flux from the inner lagoon sediments in the summer months (Newton et al., 2003) which reaches 761 μmol m^{-2} d^{-1} (Falcão and Vale, 1990a) and freshwater inputs during the rainy season (Newton, 1995).

Station 1, in the inner channel close to Faro, was usually undersaturated with respect to oxygen but hypoxia was not observed at any time. Afternoon supersaturation of dissolved oxygen and night-time oxygen sags were also characteristic of station 0, the shallow inner part of the western lagoon. The organic matter and nutrient loading in sewage effluents increases the microbial consumption of oxygen. The dissolved oxygen percentage saturation should not fall below 80% to maintain a healthy biota, and some nutrients such as ammonium and nitrite can be toxic in high concentrations. Values below 50% for dissolved oxygen percentage saturation may be expected during the summer nights over dense beds of *Zostera* and *Enteromorpha* (Cunha, 1990). Nevertheless, this shallow lagoon does not appear to become stratified (Newton and Mudge, 2003) so there is no persistent hypoxic or anoxic bottom water. However, there is a wide occurrence of subsurface anoxic sediments even in sandy areas and evidence of gas evolution, including hydrogen sulphide.

Deterioration of water quality in the Ria Formosa would affect the lagoon as a regional resource important for its ecological, economic and recreational value. At present there is no widespread industrialization in the area around the Ria Formosa, so the threat from industrial effluents is small. Rapid urbanization, however, has placed an increasing stress on the lagoon mainly because of the disposal of domestic sewage, much of which has poor treatment (Newton et al., 2003). Contamination may directly affect fauna and flora living in that water through lethal and sub-lethal effects and can modify their interrelationships and the community structure (Austen et al., 1989). Decreased species diversity (Austen et al., 1989) and ultimately mass mortality of the biota are possible consequences of eutrophication (UNESCO, 1988). Such incidents with massive mortalities in the clam beds and of fish were recorded in 1991 in Faro and in August 1994 near Olhão and at Ludo-Ancão, west of station 0. Contamination of the lagoon by pathogenic micro-organisms where people bathe and where bivalves are harvested, further represents a public heath risk.

European Union environmental legislation includes the Urban Waste Water Treatment Directive and the Nitrate Directive. The implementation of these Directives has caused considerable changes, especially in phosphorus loading and N:P ratios, in many European coastal waters in the last 15 years of the 20th Century. Implementation of the Urban Waste Water Treatment Directive has been particularly effective in the reduction of phosphorus inputs to the coastal zone (EEA, 2003). However, the implementation of the Nitrate Directive has not resulted in as significant a decrease in nitrate concentrations.

In the case of the Ria Formosa, the construction of several sewage treatment plants (ETAR) in the vicinity of Faro and Olhao, the main urban centers, has significantly reduced the coliform bacteria counts for the Ria Formosa (Dionisio et al., 2000). However, tertiary treatment needs to be implemented to significantly reduce the inputs of phosphorus and nitrogen.

Time trends and historical data can provide useful background information when assessing the effectiveness of management measures such as sewage treatment plants. Management changes in the Ria Formosa include the construction of Urban Waste Water Treatment plants, dredging and the opening of a new inlet in the western part of the lagoon. The Urban Waste Water Treatment plants should lower the overall inputs of nutrients from domestic sewage, especially once tertiary treatment is implemented. Dredging typically mobilizes both nutrients and metals that are found in higher concentrations in the sediments. However, the deepening of the channels can improve the tidal dilution and flushing of the nutrients. The opening of a new inlet in the west of the lagoon should also improve the tidal dilution and flushing of the nutrients.

Ecological processes also affect the uptake, removal and export of nutrients. Important components of the ecosystem of the Ria Formosa include phytoplankton (Morais et al., 2003) microphytobenthos and macroalgae (Machas et al., 2003), macrophyte population (Silva and Santos, 2003), shellfish productivity (Gamito, 1997) secondary productivity of benthos (Sprung, 1994), and fisheries (Santos et al., 1996).

The overall primary production in the Ria Formosa is due to the combined effect of phytoplankton (Icely et al., in press; Loureiro et al., in press-a), microphytobenthos macroalgae, macrophytes, and salt marsh plants (Padinha et al., 2000). A decrease in overall nutrient inputs due to the implementation of management measures may in theory decrease the primary productivity of the system (Icely et al., in press). However, the stoichiometry of the nutrients is another important factor and shifts in nutrient ratios may result in shifts in the plant population (Loureiro et al., in press-b). Processes such as dredging can physically damage important components of the plant ecosystem such as the seagrasses in the Ria Formosa, and also temporarily increase turbidity. Seagrasses can also be affected by the growth of epiphytic algae. Dredging also affects the bivalves (Chicharo et al., 2002; Falcão and Vale, 2003). The micro-phytobenthos is an important component of the primary producers in shallow systems with high irradiance, such as the Ria Formosa, and are also disrupted by physical processes such as dredging and shifts in the stoichiometry, especially affecting the pinnate diatoms population when Silicate availability is low.

The tidal exchange of phytoplankton with the adjacent coastal waters through the inlets is likely to be enhanced by dredging and the new inlet in the western lagoon.

The secondary productivity of the benthos, the shellfish productivity of farmed bivalves, and fisheries of the Ria Formosa also depend on the primary productivity of the system.

Coastal lagoons in southern Europe include Arcachon, the Ria de Aveiro and the Ria Formosa on the Atlantic. Of these, the Ria Formosa has the smallest input of freshwater. There are many coastal lagoon systems in the Mediterranean such as the Mar Menor, the Etang de Thau, the Sacca di Goro and Venice. The tidal flushing and physical mixing in the Ria Formosa is much greater than in these microtidal lagoons. Although the Ria Formosa is a region of restricted exchange and mesotidal, flushing and dilution are important in limiting the impacts of nutrient inputs (Newton and Icely, 2004). The accumulation and ecological effects of nutrients and stoichiometry are therefore less pronounced in the Ria Formosa as compared to the Mediterranean lagoons.

The historical context described in this paper provides a background for the assessment of the efficacy of the management of the Ria Formosa and its comparison with similar systems in southern Europe during the period of implementation of the Water Framework Directive.

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