



Boundary conditions for the European Water Framework Directive in the Ria Formosa lagoon, Portugal (physico-chemical and phytoplankton quality elements)

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Abstract

The dynamics between nutrients, the microplankton assemblage and physical factors were evaluated in the Ria Formosa (S. Portugal) coastal lagoon. Water samples were collected from Ramalhete and Ponte within the lagoon and compared with the conditions at Barra, an oceanic inlet. The two lagoon stations represent the boundary conditions of two different water bodies that have been registered as intercalibration sites for the European Water Framework Directive. Sampling coincided with high and low water conditions, at the summer and winter solstice, and at the spring and autumn equinox between June 2001 and July 2002. Chlorophyll *a* values, with a maximum of $5.1 \mu\text{g l}^{-1}$ during growing season, were lower than those reported for similar systems. The maximal winter values of $5.99 \mu\text{M}$ for total inorganic nitrogen, $0.53 \mu\text{M}$ for phosphate, and $6.34 \mu\text{M}$ for silicate, were also lower than previously reported for this area. Microplankton peaked during the summer solstices of June 2001 and July 2002, with maximal abundances of $12 \times 10^5 \text{ cells l}^{-1}$ and $7 \times 10^5 \text{ cells l}^{-1}$ for total microplankton, respectively: these communities were dominated by diatoms. At the autumn and spring equinox (September 2001 and April 2002), the maximal abundances were $4.9 \times 10^5 \text{ cells l}^{-1}$ and $2.6 \times 10^5 \text{ cells l}^{-1}$ total microplankton, respectively: these communities were more evenly distributed between diatoms, dinoflagellates, nanoflagellates and ciliates. At the winter solstice (December 2001), the microplankton were at their lowest with a maximal abundance of $1.0 \times 10^5 \text{ cells l}^{-1}$: these communities were dominated by small organisms, particularly nanoflagellates. The oceanic microplankton community at the Barra inlet was generally less numerous and differed in composition from the lagoonal communities at Ramalhete and Ponte. Multivariate analysis clustered the microplankton assemblage according to season. Changes in the microplankton community were related mainly to variations in temperature, solar radiation and salinity, and to the availability of the reduced forms of nitrogen. The differences between the parameters observed at the entrance of the lagoon during the summer solstice of 2001 and 2002 may be due, respectively, to the colder upwelled water during 2001 and the much warmer water observed in 2002. Nutrient enrichment was possible both from coastal waters and from internal lagoonal processes. Consequent accumulation of biomass may occur in inner regions where water circulation is restricted, which may lead to episodes of water quality degradation. This study does not alter the boundary conditions for Ramalhete and Ponte registered at the European Commission, respectively, as 'good/moderate' and 'high/good'.

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1. Introduction

Coastal lagoons have high physico-chemical and biological variability over both spatial and temporal scales. This

variability is produced by strong salinity and temperature gradients, limited volumes, shallow waters, close coupling between benthic and pelagic domains, and restricted connections to the adjacent sea (Nixon, 1982; Nuccio et al., 2003). Lagoon habitats are increasingly vulnerable to uncontrolled human activity (Vallejo, 1982), such as increasing nutrient loads from terrestrial watersheds (Bricker et al., 1999;

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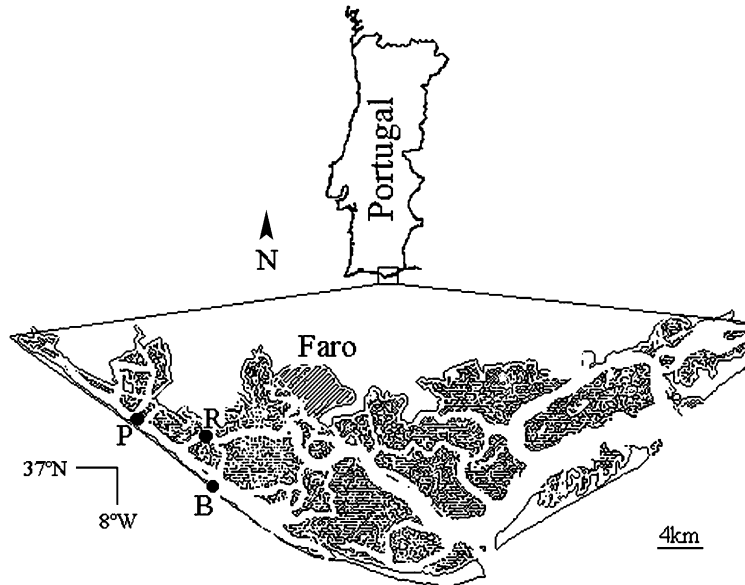


Fig. 1. Sampling stations in the Ria Formosa coastal lagoon (S. Portugal): B = Barra, R = Ramalhete, P = Ponte (modified from Fig. 1 in Loureiro et al., 2005b).

Boesch and Brinsfield, 2000; Skei et al., 2000; Cloern, 2001) that can induce anthropogenic eutrophication. Indeed, one of the first publications on the detrimental effects of eutrophication in a marine ecosystem was on the shallow coastal lagoon of Moriches Bay, along the south shore of Long Island, New York (Nixon, 1995).

Regulatory pressure is increasingly an option taken by many countries (N.R.C., 2000; E.C., 2000) to redress the environmental degradation of water resources. In the European Community (E.C.), the Water Framework Directive (WFD; E.C., 2000) is the legal mechanism for maintaining and improving the ecological quality of fresh and coastal waters. This improvement of quality includes preventing, or limiting, anthropogenic eutrophication, that has been defined under the Urban Waste Water Directive (E.C., 1991) as: “enrichment of water by nutrients especially compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms and the quality of the water concerned”. The WFD proscribes monitoring programmes to establish the typology and the quality of water bodies. For ‘surveillance’ monitoring, the Directive suggests an interval of three months for physico-chemical quality elements including salinity, temperature, oxygen and nutrients; but for biological quality elements the intervals are much greater, six months for phytoplankton and three years for macroalgae, invertebrates and fish. However, at sites where environmental objectives may not be achieved, ‘operational’ monitoring should occur at increased frequencies. In cases where accidental pollution has occurred, or the reasons for poor ecological status are unknown, ‘investigative’ monitoring should be instigated at the frequencies necessary to provide the solutions. Finally, the Directive states that monitoring must be carried out at all sites with protected status.

Borja (2005) has noted that relatively little has been published on the European WFD in relation to coastal waters.

This study examines the implementation of the WFD for the Ria Formosa (Fig. 1), an important lagoon with protected status in southern Portugal. Under the Common Implementation Strategy (CIS) of the WFD (Vincent et al., 2002), the Ria typology corresponds to a mesotidal, sheltered Atlantic coast (Bettencourt et al., 2004). There is a body of historical data (see references in Falcão and Vale, 2003; Newton and Mudge, 2005) that has been evaluated:

- (1) to identify the susceptibility to eutrophication of the lagoon (Newton et al., 2003);
- (2) to establish the boundaries for water bodies within the lagoon (Ferreira et al., 2005).

On the basis of this historical data, the sites of Ramalhete (No. 1261, Site Code C3979¹) and Ponte (No. 1259, Site Code C3978¹) in the Ria Formosa (Fig. 1) have been registered by the Commission of European Communities¹ as part of the European list of inter-calibration sites for the WFD, and have been classified with an ecological status of good/moderate and high/good, respectively. In this study, the boundary conditions for physico-chemical parameters have been compared at these two sites with the conditions at the oceanic inlet of Barra (Fig. 1) to assess whether the frequency of sampling proposed by the WFD is adequate to monitor changes in the Ria Formosa.

Phytoplankton is an important component of the biological quality elements considered by the WFD (E.C., 2000). In coastal waters, phytoplankters are generally efficient filters for nutrient inputs from terrestrial watersheds (Jickells, 1998) and will respond rapidly to biotic and abiotic changes (Harris, 1986;

¹ The Commission of European Communities took the decision on 17th August 2005 to establish a register of sites to form an intercalibration network in accordance with Directive 2000/60/EC of the European Parliaments and of the Council.

Niemkiewicz and Wrozkloek, 1998). However, in the case of the Ria Formosa there is little published work on changes in the phytoplankton community (Marques et al., 1996; Moita and Vilarinho, 1999). Although the WFD recommends sampling phytoplankton at six monthly intervals, in this study the phytoplankton were sampled at the three monthly intervals from the same locations used for the physico-chemical parameters; with the objective of providing an initial baseline for the community structure of the phytoplankton at Ramalhete, Ponte and Barra (Fig. 1); and also to evaluate the dynamics between the micro-pelagic community and nutrient concentrations.

1.1. Study area

Fig. 1 shows the location of the Ria Formosa lagoon along the south coast of Portugal. Nationally, it has been recognised as a Natural Park since 1987. Internationally, it forms part of the Natura 2000 European network for nature conservation, it is a Ramsar wetland and it is included in the Special Bird Protection Area (European Directive 79/409/EEC). It is 55 km long with an area reaching 160 km², of which one third is intertidal, with an average channel depth of 3.5 m (Falcão and Vale, 1990). The lagoon is bordered by a string of sand dunes and interacts with the surrounding oceanic waters via several inlets. At each tide, there is a 50–75% exchange of water mass (Tett et al., 2003). Tidal range varies from 2.8 m to 1.3 m at spring and neap tides, respectively. There are no major freshwater discharges in the western lagoon, although episodic run-off occurs from rainfall during the winter season. Salinity ranges from 13 to 36.5, and temperature from 12 to 27 °C (Newton and Mudge, 2003).

The concentrations of nutrients in the lagoon and the coastal waters are probably influenced by fluctuations in currents along the southern coastal shelf of Portugal. An upwelling of nutrient-rich water is induced along this shelf by westerly winds. There is also seasonal upwelling, from May to September driven by northerly winds down the west coast. These nutrient-rich waters (e.g. Loureiro et al., 2005a) may flood the southern shelf after flowing counter-clockwise around Cabo São Vicente, at the south-western tip of Europe (Fiúza, 1983; Sousa and Bricaud, 1992). The southern shelf is also influenced by the presence of a warm coastal countercurrent (CCC) that originates from the Gulf of Cádiz. The progress of the CCC along the shelf towards Cabo São Vicente depends on pressure gradients and wind forcing (Relvas and Barton, 2002). Apart from the exchange with adjacent coastal waters (Falcão and Vale, 2003; Newton and Mudge, 2005), nutrients are also imported from urban wastewater treatment plants as point sources, and from agricultural run-off as non-point sources (Ferreira et al., 2003; Newton et al., 2003). Nutrients are additionally supplied by tidal pumping from sediments within the lagoon (Falcão and Vale, 1990).

The lagoon is an important economic resource for fishing, aquaculture, salt extraction and tourism (Newton and Mudge, 2003; Santos et al., 2004), with anthropogenic pressure increasing during the summer high season because of tourism. Aquaculture is affected by episodes of anoxia (Gamito, 1997a) and by extensive mats of green algae formed during the winter

(Reis and Sprung, 1995). Accumulation of biotoxins in clams and consequent human intoxication has been observed in the eastern lagoon (Vale and Sampayo, 1999). Macroalgae and macrophytes are reported as the major sources of organic carbon in the Ria (Sprung, 1994; Santos et al., 2004).

The sampling stations represent contrasting conditions:

- (1) Ramalhete has a muddy substrate, with a complex circulation pattern where the water exchanges are slower than at the other two sites (Newton and Mudge, 2003). The Ramalhete channel receives the effluent from the Urban Waste Water Treatment (UWWT) for the urban conurbation of Faro, and is adjacent to a busy airport (R in Fig. 1). The site is affected by recreational activities between Faro City and the barrier islands of the lagoon; and by bivalve culture;
- (2) Ponte has a sandy–muddy substrate. It is located on a channel that links the Barra oceanic inlet with the Ancão basin at the blind-end of the western lagoon (P in Fig. 1). The Ancão basin receives the effluent from the golf courses of the luxury tourist development at Quinta do Lago, and from intensive agriculture. This site is also affected generally by recreational and touristic activities, and by bivalve culture.
- (3) Barra has a sandy substrate and is the site for the opening of an artificial inlet in 1997 on the west lagoon (B in Fig. 1) during the INDIA (Inlet Dynamics Initiative: Algarve) project (Williams et al., 2003).

2. Material and methods

2.1. Sampling

The sampling interval was based on the three-monthly period proposed in Annex V by the WFD for ‘surveillance’ monitoring. Sampling coincided with low water (LW), and high water (HW) close to the extreme “neap” tides of the summer (13.06.2001; 03.07.2002) and winter (08.12.2001) solstice, and the extreme “spring” tides of the spring (17.04.2002) and autumn equinox (18.09.2001). LW samples characterised residual lagoon water influenced by internal lagoon dynamics, whereas HW samples illustrated the influence of the adjacent coastal waters. These situations were chosen to represent seasonal and tidal “extremes”, thus exploring the variability of conditions to optimize sampling effort in WFD monitoring plans.

Surface water was collected and filtered through a 200 µm mesh to exclude large organisms and particles. Samples for chlorophyll *a* (chl *a*) were filtered using Whatman GF/F filters, and frozen until pigments were extracted by acetone for determination by fluorometrical analysis (JGOFS, 1994). Nutrient samples were frozen at –20 °C and subsequently analysed by standard colourmetric techniques (Grasshoff et al., 1983) for nitrate (N-NO₃⁻), nitrite (N-NO₂⁻), ammonium (N-NH₄⁺), phosphate (P-PO₄³⁻) and silicate (Si-SiO₄²⁻). Dissolved oxygen (D.O.) was estimated by a standard Winkler titration (Strickland and Parsons, 1972; Bryan et al., 1976) using a Brand

microburette. Oxygen saturation (%) was derived from standard equations (Aminot and Chaussepied, 1983). Temperature and salinity data were recorded with a WTM-LF197-S profile conductivity meter with a TetraCon 325 standard conductivity cell. Standard seawater (International Oceanographic Commission) was used for calibration at the beginning and end of each sampling period. Total daily solar irradiance (kJ m^{-2}) was recorded by the Portuguese Instituto de Meteorologia (IM) at the Faro Airport meteorological station ($07^{\circ}58'W$, $37^{\circ}01'N$, 8m).

2.2. Microscopic identification

Samples for microscopy were fixed with Lugol's solution and subsequently settled in sediment chambers for identification of the microplanktonic assemblage (Tomas, 1997) and for the determination of their abundance (Utermöhl, 1958) using a Zeiss Axiovert 25 inverted microscope. Organisms were generally classified to genus level with the assemblage divided into four major taxonomic components: diatoms (Bacillariophyceae), dinoflagellates (Dinophyceae), ciliates (Ciliatae) and nanoflagellates. Wherever possible the nanoflagellates were separated into Cryptophyceae, Dictyochophyceae, and Euglenophyceae but, where this was not possible, they were enumerated as unidentified nanoflagellates.

2.3. Statistical treatment

PRIMER[®] software (Plymouth Routines In Multivariate Ecological Research) was used for statistical analysis of the microplanktonic assemblage (Clarke, 1993). Each sample was assumed to be representative of its time of collection, station and tidal condition (Clarke and Warwick, 2001).

Abundances were transformed into square-roots to determine the Bray–Curtis similarity matrix from which hierarchical agglomerative clustering (group-average linking) and multi-dimensional scaling (MDS) were used to assess natural

groupings of samples and their relation to abiotic factors. The ANOSIM routine evaluated the statistical difference between the a priori sampling groups (June, September and December 2001; April and July 2002). The SIMPER routine tested for the contribution of taxa to the dissimilarities between these groupings. Several ecological indices were calculated to evaluate the characteristics of the community structure, including: total number of taxa, total number of individuals, Margalef's richness index, Pielou's evenness, and Shannon–Wiener index. The identification of cells down to genus level and wider groups did not account for the intraspecific variability of taxa, which could have led to an underestimation of diversity values. Nevertheless, relative comparison of such indices still reflected the seasonal diversity oscillation and consequent modification of the microplanktonic community structure (Nuccio et al., 2003). STATISTICA[®] software was used for parametric and non-parametric tests.

3. Results

3.1. Variations of measured parameters

3.1.1. Absolute variations

The range and mean values of physical, chemical and biological parameters measured, as well as chlorophyll *a*, measured during the survey are summarised in Table 1 for comparison with historical data. Variations between the overall mean values and those estimated for the individual stations demonstrated differences between the three sites. The highest mean values were observed: at the Ponte lagoon station for temperature, chl *a*, N-NO_3^- , DIN (dissolved inorganic nitrogen), P-PO_4^{3-} , Si-SiO_4^{2-} and N:P; at the Ramalhete lagoon station for salinity, chl *a*, N-NH_4^+ , N-NO_2^- and N:Si; and at the Barra oceanic inlet for dissolved oxygen and oxygen saturation. The lowest mean values occurred at the Barra for most of the parameters, except for dissolved oxygen and oxygen saturation, which were lowest at Ramalhete.

Table 1
Mean, minimum and maximum values of the parameters measured at the Ria Formosa lagoon between June 2001 and July 2002, at the sampling stations described in the text. Chl *a* = chlorophyll *a*, DIN = dissolved inorganic nitrogen ($\text{NO}_3^- + \text{NO}_2^- + \text{NH}_4^+$), Temp. = temperature, D.O. = dissolved oxygen, O_2 sat. = oxygen saturation

Parameters	Whole study period			Sampling stations								
	Mean	Min	Max	Barra			Ramalhete			Ponte		
				Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Temp. (°C)	20.3	14.5	24.7	19.8	15.9	22.9	20.4	14.5	23.2	20.6	15.5	24.7
Salinity	36.4	35.5	37.0	36.3	35.5	36.9	36.5	35.6	37.0	36.4	35.7	37.0
Chl <i>a</i> ($\mu\text{g l}^{-1}$)	1.7	0.1	5.1	1.4	0.1	3.0	1.8	0.7	4.2	1.8	0.4	5.1
N-NO_3^- (μM)	4.1	0.4	9.7	3.2	0.4	9.7	4.2	0.8	9.3	5.0	2.7	9.0
N-NO_2^- (μM)	0.13	0.02	0.41	0.11	0.02	0.41	0.14	0.08	0.25	0.12	0.06	0.25
N-NH_4^+ (μM)	1.15	0.08	4.89	0.87	0.08	4.64	1.31	0.09	4.89	1.26	0.09	3.69
DIN (μM)	5.4	1.0	14.3	4.2	1.0	11.2	5.6	2.3	14.3	6.3	3.1	12.2
P-PO_4^{3-} (μM)	0.49	0.14	1.25	0.35	0.14	0.75	0.52	0.27	0.80	0.60	0.21	1.25
Si-SiO_4^{2-} (μM)	4.0	0.4	15.4	2.3	0.4	5.3	3.5	1.2	7.6	6.1	0.5	15.4
N:P	12	3	28	12	3	28	10	5	20	14	4	28
N:Si	2.3	0.5	9.7	2	0.7	4.3	2.6	0.5	9.7	2.2	0.5	6
D.O. (mg l^{-1})	7.1	5.4	8.3	7.3	6.3	8.2	6.9	5.7	8.2	7.0	5.4	8.3
O_2 sat. (%)	97	76	111	99	89	109	95	81	111	96	76	108

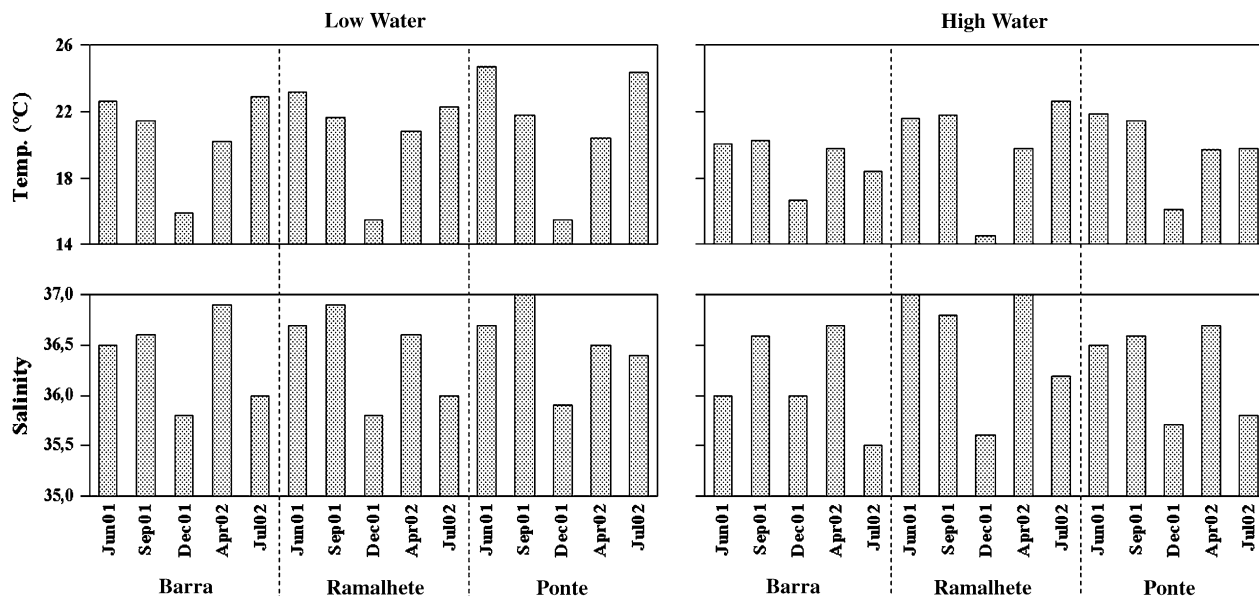


Fig. 2. Temperature and salinity values registered during sampling at the Barra, Ramalhete and Ponte stations of the Ria Formosa lagoon, at low and high water.

3.1.2. Sampling variations

Figs. 2, 3 and 4 illustrate seasonal, spatial and tidal values measured for the physical, chemical and biological parameters. In general, the seasonal difference between most of the parameters was statistically significant on the basis of the Kruskal–Wallis test including: temperature and salinity ($p < 0.001$), chlorophyll *a* ($p = 0.0002$), reduced forms of nitrogen ($p < 0.03$), and oxygen ($p < 0.05$). There were no seasonally significant differences between the values for phosphate and silicate.

Spatial variation has been demonstrated in Section 3.1.1 for the absolute mean values of the data set, but there are also patterns in the tidal variation within the periodic data from the sampling campaigns. In the case of temperature and salinity (Fig. 2), the greatest variation between LW and HW occurred during the summer solstice in 2001 and 2002, with the warmest water observed at LW at all the sites, apart from Ramalhete in July, where the values were similar between LW and HW. The coldest waters were observed at LW for Barra and Ponte, and HW for Ramalhete during the winter solstice. In general, salinity was less variable than temperature but the pattern for LW and HW for the three sites was relatively similar between the two parameters. When there were differences, they tended to occur at Ramalhete where, for example, at LW in June 2001 the temperature was higher and the salinity was lower than at HW.

In the case of chl *a* (Fig. 3), the maximal values and the greatest differences at different tidal conditions occurred at the autumn equinox in 2001 (September). The inorganic nitrogenous compounds varied between LW and HW depending on the compound and the time of the year. Thus, ammonium was generally higher at LW at all the three sites throughout the year. Nitrite was higher at LW throughout the year at the Ponte, but only in December 2001, April 2002 and July 2002 at the Barra, and only in September 2001 at Ramalhete. Nitrate was higher at LW in December 2001, April 2002 and July 2002 at

the three sites, and additionally in September for Ponte and Ramalhete. It was striking that the lowest and highest values for nitrate throughout survey occurred at the oceanic inlet (Barra) at LW and HW in June 2001, respectively. Phosphate values were generally higher at LW, whilst silicate values were consistently higher at LW throughout the survey.

Both oxygen concentrations and saturation (Fig. 4) also showed a consistent pattern between the three sites with higher values at LW for the three solstice sampling campaigns, and at HW for the two equinox samplings. These patterns were related to the time of sampling with the higher values observed during the afternoon and the lower values during the morning.

3.2. Microplankton assemblage

3.2.1. Microplankton abundance changes

Table 2 shows the taxa identified during the survey of the Ria Formosa, together with their codes and their frequency of occurrence. Greater than, or equal to, 60% of the total taxa were represented by genera, or higher taxonomic groupings, of 10 diatoms, 8 dinoflagellates, 4 ciliates and 3 nanoflagellates. Fig. 5 shows that the greatest abundance of microorganisms occurred generally during LW at both the Barra and Ponte, and at HW at Ramalhete. Peaks in abundance were observed at the summer solstices of June 2001 ($12 \times 10^5 \text{ cell l}^{-1}$, Ramalhete-HW) and July 2002 ($7.1 \times 10^5 \text{ cell l}^{-1}$, Ramalhete-HW). During June (2001) and July (2002), the samples were mainly dominated by diatoms (max: $9.5 \times 10^5 \text{ cell l}^{-1}$, June 2001; Fig. 5), although ciliates were at their most numerous during June 2001 (range: $98\text{--}221 \times 10^3 \text{ cell l}^{-1}$). In September 2001 and April 2002, the assemblage was evenly distributed between diatoms (mean: $135 \times 10^3 \text{ cell l}^{-1}$, $64 \times 10^3 \text{ cell l}^{-1}$, respectively), dinoflagellates (mean: $121 \times 10^3 \text{ cell l}^{-1}$, $47 \times 10^3 \text{ cell l}^{-1}$, respectively) and nanoflagellates (mean: $122 \times 10^3 \text{ cell l}^{-1}$, $36 \times 10^3 \text{ cell l}^{-1}$, respectively). Nanoflagellates generally

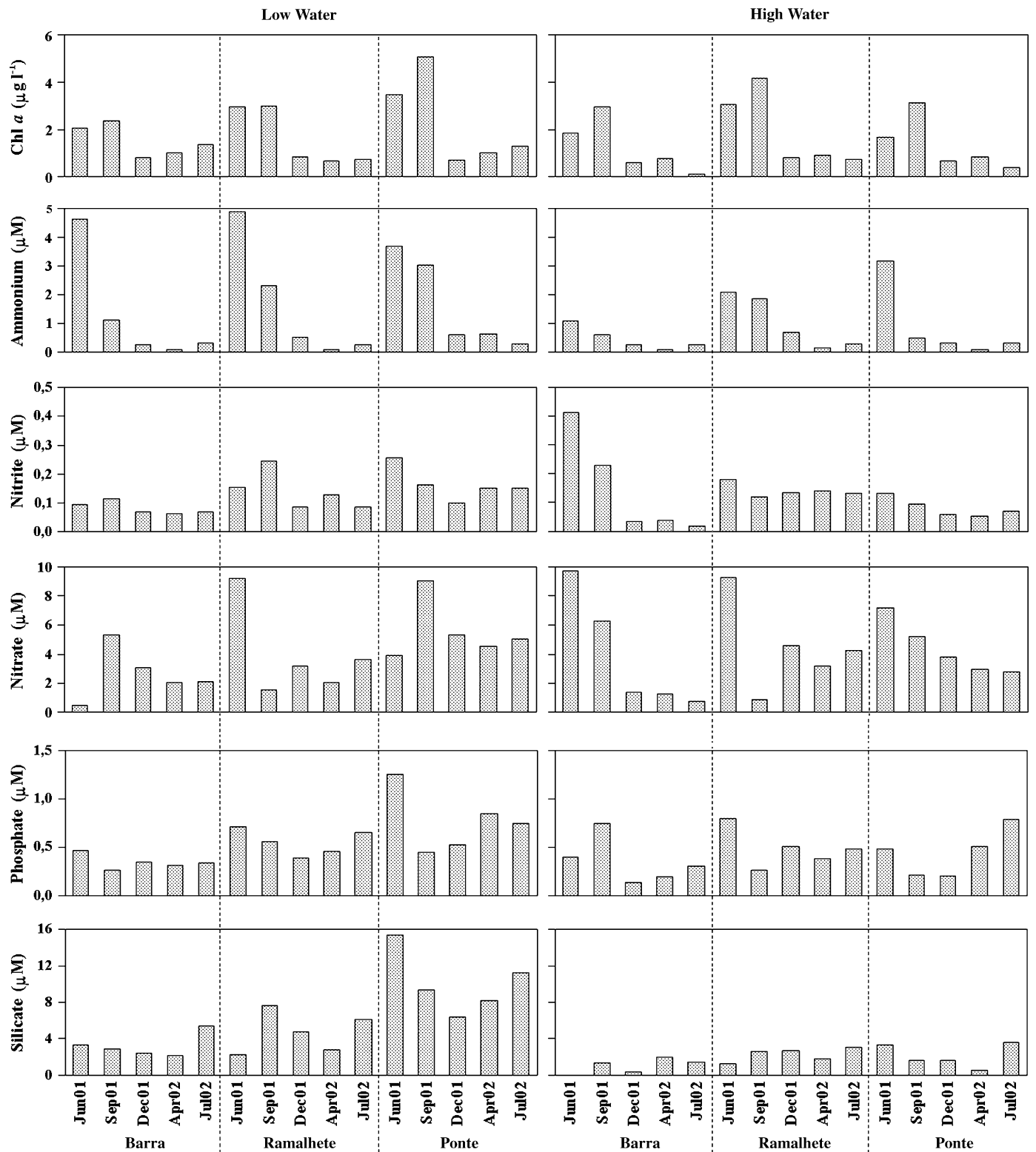


Fig. 3. Chl a , ammonium, nitrate, nitrite, phosphate and silicate concentrations measured during sampling at the Barra, Ramalhete and Ponte stations of the Ria Formosa lagoon, at low and high water.

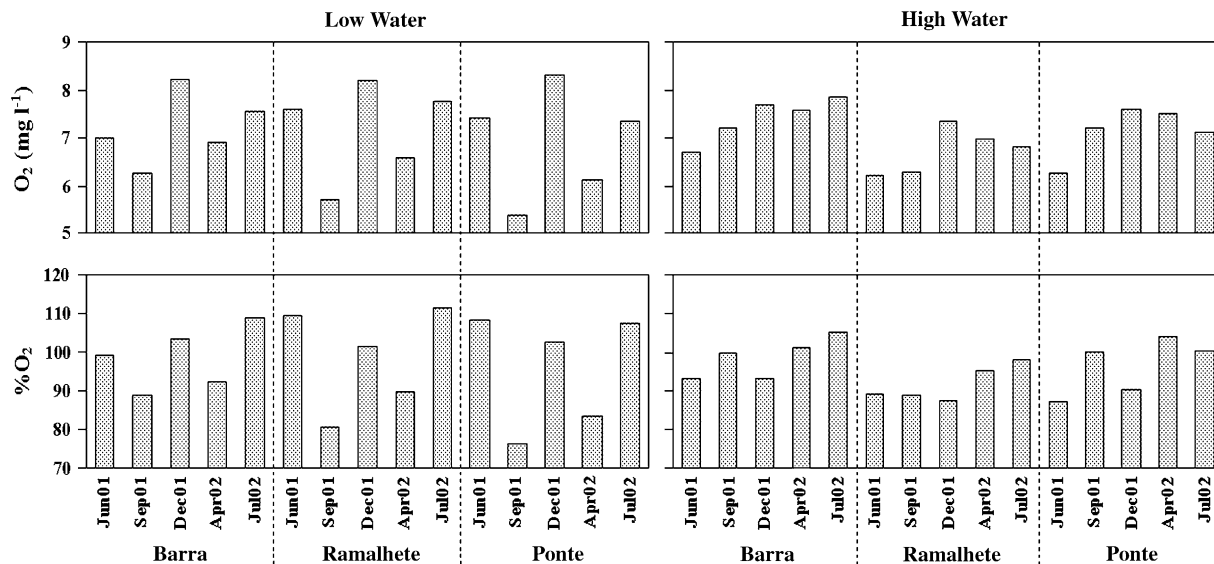


Fig. 4. Oxygen concentration and saturation measured during sampling at the Barra, Ramalhete and Ponte stations of the Ria Formosa lagoon, at low and high water. Bars on oxygen concentration columns correspond to standard errors; bars are not visible when the errors are low.

dominated the plankton in December 2001 (max: $62 \times 10^3 \text{ cell l}^{-1}$) when the microplankton abundance at all three sites was at its lowest (min: $34 \times 10^3 \text{ cell l}^{-1}$).

3.2.2. Statistical community analysis

The dendrogram obtained by cluster analysis (Fig. 6) associated the samples on the basis of seasonal differences. The assemblage for the winter solstice (December 2001) showed a strong separation from the other groups. At 50% of the Bray–Curtis similarity index, three clusters were evident: the summer solstice 2001 (June), the winter solstice, and a third cluster which linked samples from the autumn equinox (September 2001), the spring equinox (April 2002) and the summer solstice 2002 (July). When the similarity level was increased to 55%, the assemblage divided further into a total of six groups. The Barra-HW assemblage separated from its seasonal cluster during the solstice campaigns (June, December, July).

One-way ANOSIM tests (Table 3) on the similarity matrices for the abundances (transformed to square roots) from the distinct a priori group of samples (June 2001, September 2001, December 2001, April 2002 and July 2002), demonstrated that the differences in the community structure were statistically significant (global $R = 0.82$). Specific R values for each pairwise comparison showed that the largest community separation was between summer solstice 2001 and spring equinox 2002 samples ($R = 0.99$), whereas the weakest community separation was between the autumn equinox 2001 and the summer solstice 2002 ($R = 0.53$).

The similarity percentage analysis (SIMPER) on the abundances (transformed to square roots) revealed the most discriminating taxa between the different microplanktonic groups, as well as the indicator taxa for each of the groups. The spatial and seasonal distribution of the principle taxa are represented in Fig. 7. Thus, the characteristic groups for: the summer solstice in 2001 were *Thalassiosira* spp., cryptomonads, and

ciliates; the autumn equinox in 2001 were unidentified nanoflagellates, *Chaetoceros* spp., small ($<20 \mu\text{m}$) unidentified dinoflagellates, *Gymnodinium* + *Gyrodinium* spp., *Nitzschia* spp. and *Alexandrium* spp.; the winter solstice in 2001 were nanoflagellates, cryptomonads, Oligotrichida and *Gymnodinium* + *Gyrodinium* spp.; the spring equinox in 2002 were *Leptocylindrus* spp., *Pseudo-nitzschia* spp., *Guinardia* spp. and *Scrippsiella* spp.; and finally, the summer solstice in 2002 were Eutreptiaceae taxa, *Thalassiosira* spp. (in common with the previous summer solstice), and unidentified nanoflagellates (in common with the previous autumn equinox).

3.3. Biotic and abiotic relations

In Fig. 8, environmental variables (as bubble plots) are superimposed on the MDS ordination, in order to relate the abiotic variables to the microplankton community. These plots confirmed the results of the cluster analysis (Fig. 6) where the samples were grouped according to the sampling season. Temperature, salinity, solar radiation and ammonium parameters showed a similar distribution to total microplankton, dividing the biotic clusters. However, the remaining variables did not appear to relate closely with the overall biotic structure. As a result of the patchy distribution of these residual variables, there was not a dominant gradient in these ordinations.

The results of the Spearman rank-order correlations between the microplankton assemblage and the physical, chemical and biological parameters are presented in Table 4. The total microplankton abundance was significantly ($p < 0.05$) correlated to temperature and solar radiation. A major autotrophic component would be expected by the strong correspondence between chl *a* and the total microplankton ($r_s = 0.72$, $p < 0.05$). Comparisons with the chemical parameters suggested that reduced forms of nitrogen had a high correlation with the microplankton assemblage ($r_s = 0.54$ and

Table 2
Microplanktonic taxa identified from the Ria Formosa together with their abbreviations (codes) and their frequency of occurrence during the survey. Most frequent taxa ($\geq 60\%$) are in bold-italic type

Code	Taxa	Frequency (%)	Code	Taxa	Frequency (%)
Bacillariophyceae (diatoms)			Dinophyceae (dinoflagellates)		
Centrales			Ale	<i>Alexandrium</i> spp.	50
Ast	<i>Asteromphalus</i> spp.	3	Amp	<i>Amphidinium</i> spp.	37
Bac	<i>Bacteriastrum</i> spp.	17	Cer	<i>Ceratium</i> spp.	57
Cha	<i>Chaetoceros</i> spp.	93	Din	<i>Dinophysis</i> spp.	40
Cos	<i>Coscinodiscus</i> spp.	53	Gon	<i>Gonyaulax</i> spp.	47
Dac	<i>Dactyliosolen</i> spp.	30	Gym	<i>Gymnodinium</i> spp.	83
Euc	<i>Eucampia</i> spp.	3	Gm + Gr	<i>Gymnodinium</i> + <i>Gyrodinium</i> spp.	97
Gui	<i>Guinardia</i> spp.	43	Gyr	<i>Gyrodinium</i> spp.	73
GuiF	<i>Guinardia flaccida</i>	17	Kat	<i>Katodinium</i> spp.	23
GuiS	<i>Guinardia striata</i>	30	Oxy	<i>Oxytoxum</i> spp.	3
Hem	<i>Hemiaulus</i> spp.	10	ProC	<i>Prorocentrum</i> spp.	77
Lau	<i>Lauderia</i> spp.	10	ProT	<i>Protoperdinium</i> spp.	90
Lep	<i>Leptocylindrus</i> spp.	70	Scr	<i>Scrippsiella</i> spp.	80
Lic	<i>Licmophora</i> spp.	50	Tor	<i>Torodinium</i> spp.	27
Mel	<i>Melosira</i> spp.	10	DNs	Small (<20 μm) unidentified	97
Odo	<i>Odontella</i> spp.	10	DNb	Big (>20 μm) unidentified	67
Rhi	<i>Rhizosolenia</i> spp.	77	Ciliatae		
Ske	<i>Skeletonema</i> spp.	20	Hap	Haptorida	13
Ste	<i>Stephanopyxis</i> spp.	3	Mes	Mesodiniidae	63
ThaS	<i>Thalassiosira</i> spp.	60	Oli	Oligotrichida	100
DCs	Small <20 μm unidentified	63	Tin	Tintinnina	77
DCb	Big >20 μm unidentified	63	Cil	Unidentified	90
Pennales			Cryptophyceae		
Ast	<i>Asterionellopsis</i> spp.	7	Cry	Cryptomonadales	97
Dip	<i>Diploneis bombus</i>	27	Dictyochophyceae		
Fra	<i>Fragilariopsis</i> spp.	7	Dic	Dictyochaceae (silicoflagellates)	53
Man	<i>Manguinea</i> spp.	33	Ped	Pedinellaceae	13
Meu	<i>Meuniera</i> <i>membranacea</i>	3	Nanoflagellates		
Nav	<i>Navicula</i> spp.	80	Nan	Unidentified	93
Nit	<i>Nitzschia</i> spp.	97	Euglenophyceae		
Ple	<i>Pleurosigma</i> spp.	73	Eug	Euglenaceae	27
Psn	<i>Pseudo-nitzschia</i> spp.	77	Eut	Eutreptiaceae	77
ThaN	<i>Thalassionema</i> spp.	17			
Str	<i>Striatella</i> spp.	20			
DPs	Small (<20 μm) unidentified	23			
DPb	Big (>20 μm) unidentified	47			

$r_s = 0.58$, for nitrite and ammonium, respectively), whereas phosphate had a weaker relation ($r_s = 0.37$, $p < 0.05$). Dissolved oxygen was inversely correlated with total microplankton abundance, diatoms and dinoflagellates, as well as with reduced forms of nitrogen.

3.4. Univariate indices

During the survey the total number of taxa were not significantly different (one-way ANOVA, $p = 0.21$; Fig. 9a). However, the variation of the total number of individuals (Fig. 9b) produced significant differences in the other ecological indices. The LSD Fisher test showed which of these groups differed statistically (Fig. 9). The high richness index in December (Fig. 9c) was mainly caused by the low densities observed during this period. The dominance of *Thalassiosira* spp., cryptomonads and unidentified nanoflagellates was associated with the poorer evenness

(Fig. 9d) and diversity (Fig. 9e) indices of the summer months (June 2001 and July 2002).

4. Discussion

4.1. Abiotic and biotic variability

Financial costs of monitoring programmes are high and should be therefore optimized. The current sampling programme for the Ria Formosa lagoon, based on the three monthly intervals proposed by the WFD for surveillance monitoring, complements the observations of the physical and chemical parameters made in previous studies (see references below). The measurements for temperature and salinity confirm the observations of Newton and Mudge (2003) where the trend is for warmer, hypersaline conditions in the summer due to high insolation and rapid evaporation, and for cooler,

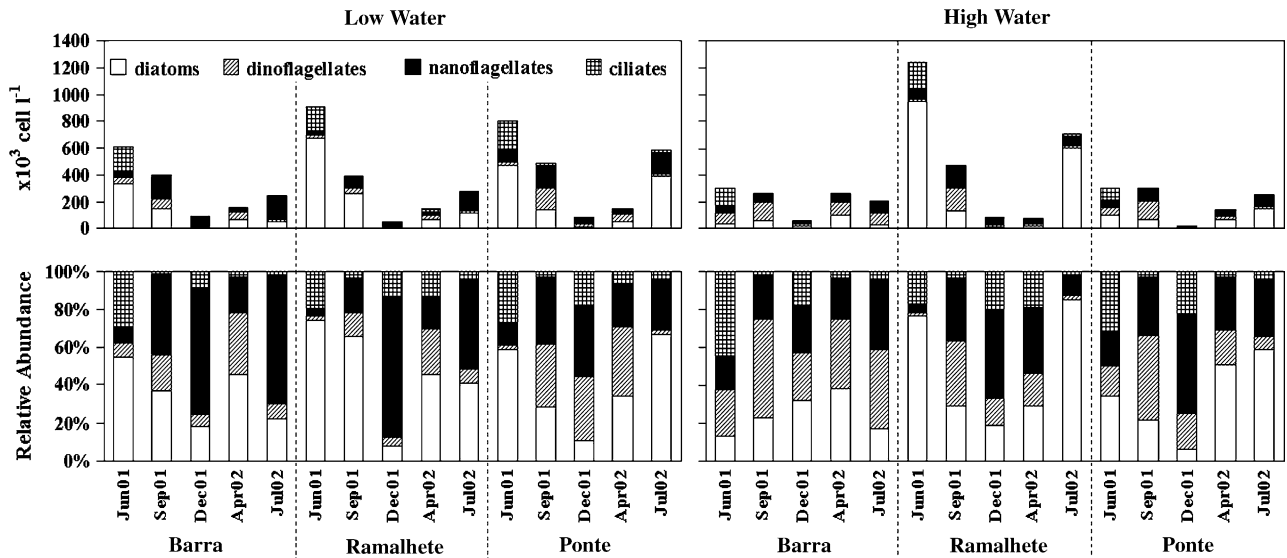


Fig. 5. Abundance and relative numbers of the microplanktonic groups identified between June 2001 and July 2002, at the Barra, Ramalhete and Ponte stations of the Ria Formosa lagoon, at low and high water.

less saline conditions in the winter produced by low insolation and freshwater runoff from the land. These conditions explain the higher temperatures and salinity at LW compared to HW, where LW reflect better the conditions within the inner lagoon, whilst HW reflects the intrusion of oceanic conditions from the adjacent coastal water. At Ramalhete, the opposite trend occurs periodically, with the higher measurements observed at HW. This observation probably reflects the complex tidal mixing and circulation pattern described for this region (Newton and Mudge, 2003). The higher salinity values measured in June 2001, in comparison with July 2002, are probably due to the influence of different coastal water masses over these periods (Fig. 10).

The ranges of chl *a* are in general agreement with previous findings for this region (Falcão and Vale, 1995; Asmus et al., 2000; Newton et al., 2003). The chl *a* pattern is mainly related to the availability of reduced nitrogen sources, temperature and salinity levels. Lower values of chl *a* at LW indicate an export to coastal waters (Falcão and Vale, 2003), with concentrations during the growing season that are generally lower compared to other similar systems (Tett et al., 2003). Low values for summer phytoplankton biomass have been associated with the presence of benthic suspension-feeding organisms in estuarine ecosystems (Alpine and Cloern, 1992). In the Ria Formosa, a significant depletion of algal concentration

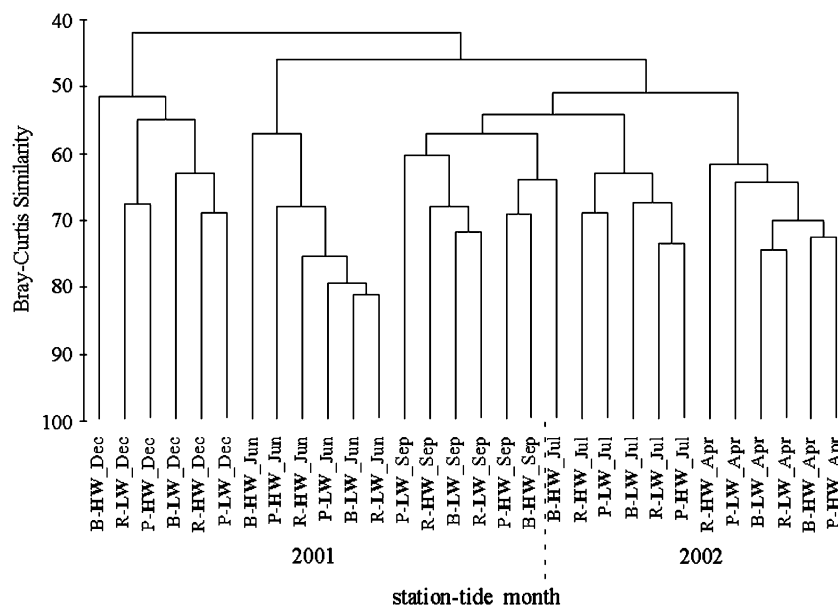


Fig. 6. Cluster dendrogram of the Bray–Curtis similarity matrix of abundances transformed into square roots. B = Barra station, R = Ramalhete station, P = Ponte station. LW = low water, HW = high water.

Table 3
Statistical differences between microplankton assemblage from the a priori seasonal groups (2001: June, September and December; 2002: April and July) based on the one-way ANOSIM test

Periods	R-pairwise test	Number of permutations	Significance level
Jun–Sep	0.88	462	0.002
Jun–Dec	0.95	462	0.002
Jun–Apr	0.99	462	0.002
Jun–Jul	0.68	462	0.002
Sep–Dec	0.96	462	0.002
Sep–Apr	0.84	462	0.002
Sep–Jul	0.53	462	0.006
Dec–Apr	0.85	462	0.002
Dec–Jul	0.89	462	0.002
Apr–Jul	0.84	462	0.002
Global R	0.82	999	0.001

in the water column at low current velocities has been related to bivalve suspension feeding (Sobral and Widdows, 2000).

The nutrient values observed in this study are within the range reported for various lagoons (Nixon, 1982), and are generally comparable with previous studies on the Ria Formosa (e.g. Newton et al., 2003, and references therein). However, DIN in this study is substantially lower than the values obtained by Newton and Mudge (2005) for the western lagoon, although in comparison with the historical data (Table 5) the values were high at Ramalhete and relatively similar at Ponte. A decrease of nitrogen inputs in the Ria Formosa waters, since

the observations of Newton and Mudge (2005), could be attributed to the improvements in water circulation (Newton and Icelly, 2002) after the opening of the artificial inlet at the Barra site in 1997 (Williams et al., 2003), and to the improvements in sewage treatment after the installation of an UWWT near Ramalhete. Also, the transcription to national legislation of the Nitrate's Directive (ND, 91/676/EEC) stimulated a new action program for the Faro region (Diário da República, 2001), with the objective to reduce water pollution by nitrates of agricultural origin.

In general, the higher concentrations of nutrients at LW support the previous observations that the lagoon exports nutrients to the coastal waters (Falcão and Vale, 2003; Newton and Mudge, 2005). However, Newton and Mudge (2005) describe periods, particularly in spring and autumn, when DIN is imported into the lagoon. In this current study, DIN is imported into the lagoon during the summer solstice of 2001, but it is exported to the coastal water during the summer solstice of 2002. A comparison of satellite images just prior to the summer samplings (Fig. 10) shows that there is a colder water mass adjacent to the coast in 2001. Physical, chemical and biological patterns of coastal transitional areas can be influenced by the dynamics of coastal upwelling events (Duxbury, 1979; Taylor, 1992; Tilstone et al., 2000; Álvarez-Borrego, 2004), especially in the dry season when freshwater supply from the land is reduced.

Falcão and Vale (1990) have suggested that phosphorus might be the limiting nutrient in the Ria Formosa on the basis of fluxes from the sediments. However, the Redfield ratio (N:P) in this study and that of Newton and Mudge (2005) support evidence from estuaries (Pennock and Sharp, 1994; Ault et al., 2000) and other lagoons (Nixon, 1982; Fong et al., 1993), that nitrogen is the limiting nutrient, at least for the western Ria Formosa. Observations from microcosm experiments described later in Section 4 also support this conclusion (Edwards et al., 2005; Loureiro et al., 2005b).

The results for oxygen concentrations essentially reflect the time of day that the samples are collected. However, at LW in September at both Ponte and Ramalhete there is undersaturation of oxygen, which would be biologically critical if it persisted. Newton and Mudge (2005) have reported persistent undersaturation of oxygen at a station near to Faro town and the Ramalhete channel. Low oxygen saturation may be responsible for some of the symptoms of water degradation that have been reported from some of the restricted regions of the lagoon where there have been marked decreases in benthic organisms (Gamito, 1997b) and substantial mortality of macroalgae (Asmus et al., 2000). The mortality of macroalgae and the consequent decomposition of the biomass may contribute to low oxygen.

4.2. Microplankton dynamics

The enumeration of the microplankton community does not account for the picoplanktonic assemblage. Pico-phytoplankton includes N₂ fixing cyanobacteria organisms, which can influence the N:P ratios (Smith, 1984). Nevertheless, in systems

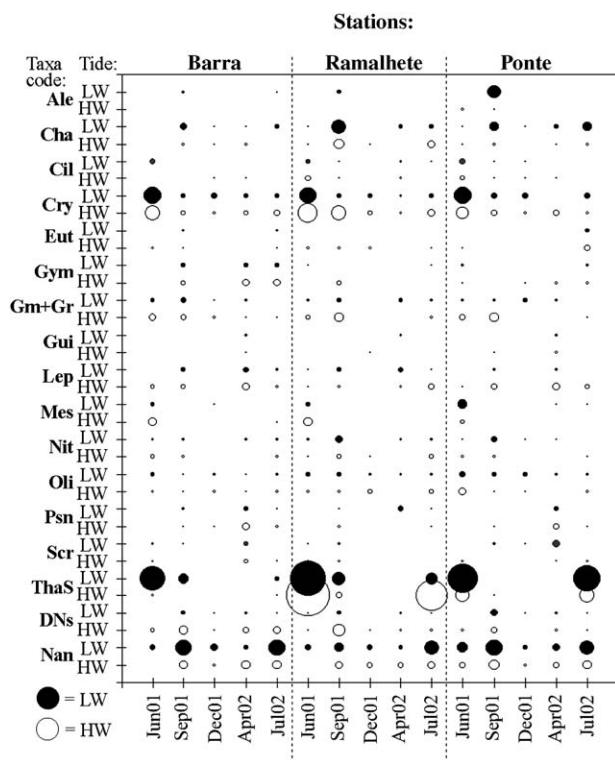


Fig. 7. Evolution of the main taxa contributing to the Bray–Curtis dissimilarities between the seasonal groups (2001: June, September and December; 2002: April and July). See Table 2 for taxa abbreviations. Circles are proportional to abundance values. LW = low water, HW = high water.

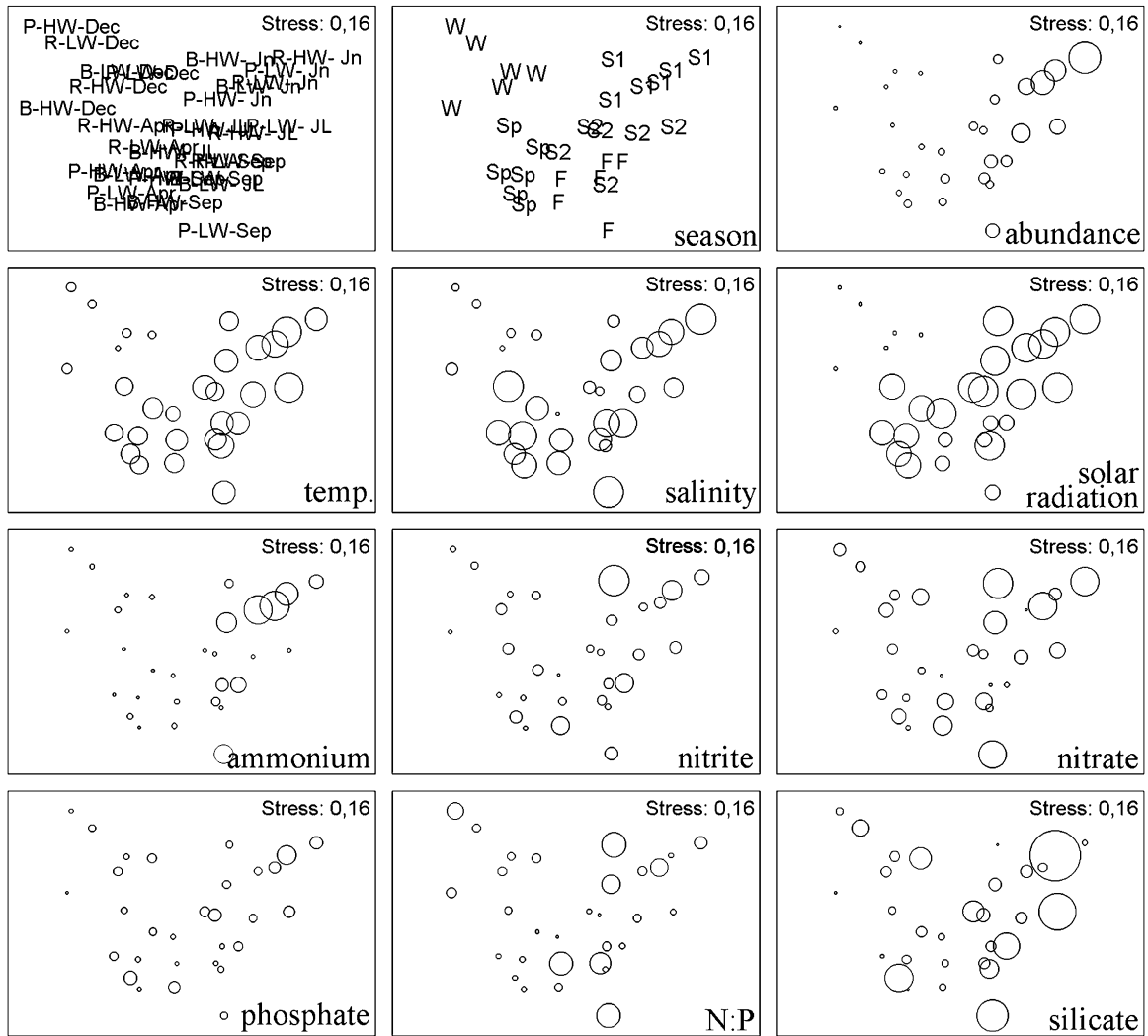


Fig. 8. Two-dimensional MDS (multi-dimensional scaling) ordination of Bray–Curtis similarities of abundance data transformed into square-root; bubbles represent the super-imposition of biotic and abiotic factors. B = Barra station, R = Ramalhete station, P = Ponte station. LW = low water, HW = high water. S1 = summer 2001, F = fall, W = winter, Sp = spring, S2 = summer 2002.

Table 4

Pairwise Spearman correlations between biological, chemical and physical parameters determined during the survey: temperature (*T*), salinity (*S*), solar radiation (light); nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), silicate (SiO_4^{2-}), dissolved oxygen (D.O.) and chlorophyll *a* (Chl *a*) concentrations; diatom ([diat]), dinoflagellate ([dino]), nanoflagellate ([nano]), ciliate ([cilia]) and total microplankton ([Total]) abundances. Bold-italic figures are significant at $p < 0.05$; *n* represents the number of samples

<i>n</i> = 30	<i>T</i>	<i>S</i>	Light	NO_3^-	NO_2^-	NH_4^+	PO_4^{3-}	SiO_4^{2-}	D.O.	Chl <i>a</i>	[diat]	[dino]	[nano]	[cilia]	[Total]
<i>T</i>	1														
<i>S</i>	0.45	1													
Light	0.63	0.04	1												
NO_3^-	0.17	0.10	-0.01	1											
NO_2^-	0.45	0.42	0.10	0.64	1										
NH_4^+	0.40	0.17	-0.02	0.44	0.62	1									
PO_4^{3-}	0.34	0.11	0.37	0.39	0.62	0.37	1								
SiO_4^{2-}	0.44	-0.04	0.16	0.07	0.32	0.34	0.48	1							
D.O.	-0.39	-0.59	-0.12	-0.23	-0.57	-0.37	-0.19	-0.15	1						
Chl <i>a</i>	0.57	0.61	-0.02	0.36	0.64	0.68	0.17	0.22	-0.56	1					
[diat]	0.81	0.55	0.58	0.13	0.41	0.39	0.44	0.27	-0.46	0.43	1				
[dino]	0.22	0.42	0.06	0.02	0.15	0.20	-0.14	-0.10	-0.45	0.46	0.22	1			
[nano]	0.54	0.11	0.37	0.12	0.19	0.26	0.10	0.37	-0.21	0.44	0.50	0.33	1		
[cilia]	0.43	0.14	0.32	0.27	0.59	0.52	0.44	0.25	-0.24	0.23	0.44	-0.10	-0.02	1	
[Total]	0.84	0.48	0.52	0.31	0.54	0.58	0.37	0.23	-0.45	0.72	0.91	0.37	0.62	0.51	1

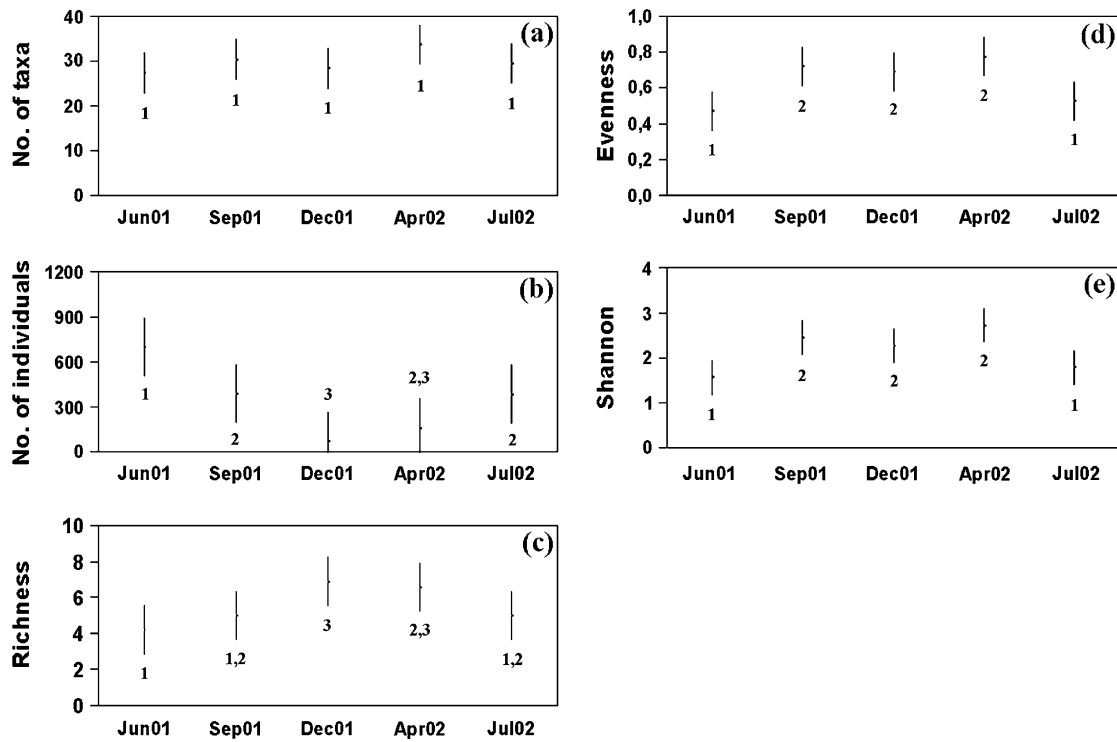


Fig. 9. Mean and 95% confidence intervals based on pooled standard deviations of univariate indices of the microplankton community. Numbers on bars represent the results of the post hoc test (LSD Fisher test): bars labelled with different numbers have significantly different means; bars with the same numbers have different means that are not significant.

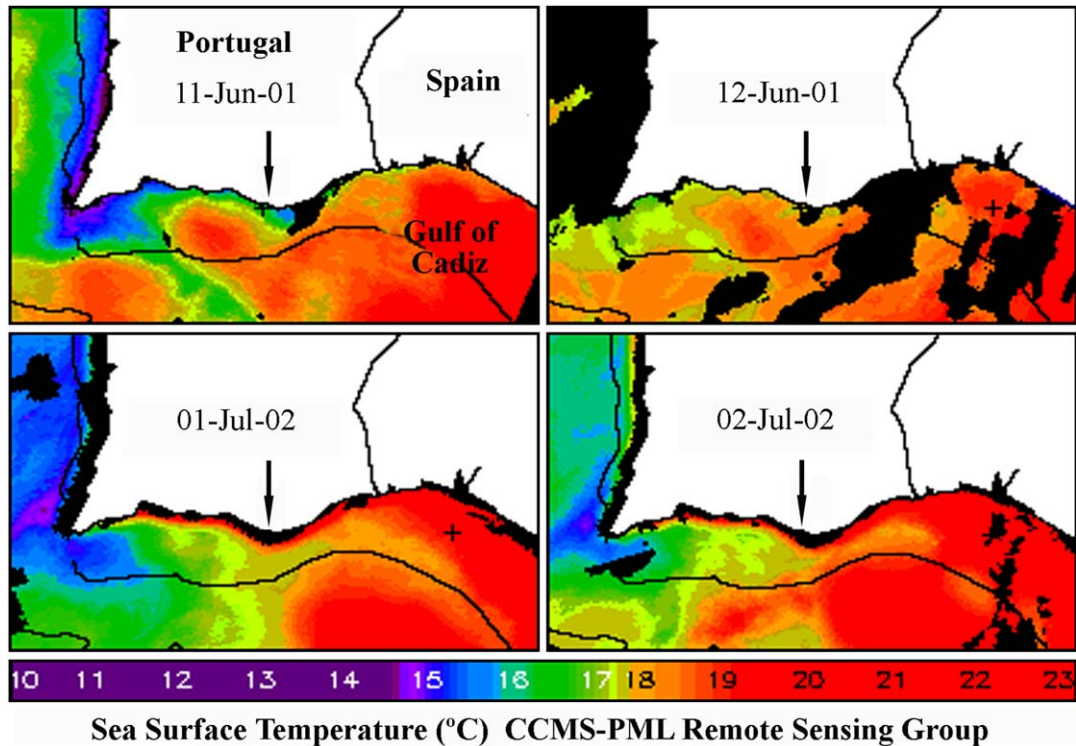


Fig. 10. Sea Surface Temperature (SST) satellite images (NOAA/AVHRR) from the South of Portugal (Algarve), processed at the Plymouth Marine Lab, UK. The dates are indicated in the image. The black arrow points to the sampling location. This image is in colour in the electronic version of this paper.

Table 5

Boundary conditions for the registered WFD intercalibration sites of Ramalhete and Ponte^a. Parameters are from the historical data set for the Ria Formosa lagoon (available at <http://www.barcaweb.com/>). Figures in parentheses and italics are from means from Table 1 of the current study. PCE, physico-chemical elements; PQE, phytoplankton quality element expressed as chlorophyll *a* (chl *a*) concentrations; –, no available data

Boundary condition		Ramalhete	Ponte
Boundary ^a		Good/moderate	High/good
Geographic location		37°0'22"N 7°58'11"W	37°0'34"N 7°59'38"W
PCE historical records	Temperature (°C)	21.5 ± 2.4 (20.4)	18.2 ± 3.6 (20.6)
	Salinity	36.3 ± 0.6 (36.5)	36.2 ± 2.6 (36.4)
	Nitrate (µM)	1.3 ± 1.8 (4.2)	5.1 ± 13.4 (5.0)
	Ammonium (µM)	1.4 ± 1.1 (1.3)	2.03 ± 2.40 (1.26)
	Nitrite (µM)	0.16 ± 0.18 (0.14)	0.30 ± 0.31 (0.12)
	DIN	2.8 ± 2.4 (5.6)	7.3 ± 17.4 (6.3)
	Phosphate (µM)	0.72 ± 0.36 (0.52)	0.73 ± 0.48 (0.6)
	Silicate (µM)	5.4 ± 2.2 (3.5)	13.5 ± 12.6 (6.1)
	D.O. (mg l ⁻¹)	7.3 ± 0.8 (6.9)	7.7 ± 1.9 (7.0)
O ₂ sat. (%)	–	94 ± 11 (96)	
PQE historical records	chl <i>a</i> (µg l ⁻¹)	1.1 ± 0.8 (1.8)	1.2 ± 0.9 (1.8)

^a See earlier footnote about European intercalibration sites for WFD.

with short water residence time, like the Ria Formosa, this influence is likely to be low (Granéli and Sundbäck, 1985).

The maximal microplankton abundance is consistently found at Ramalhete during summer samplings (June 2001 and July 2002), although this location does not have the highest nutrient concentrations. However, recent findings have shown that some algae can use dissolved organic matter as a nutrient source (Granéli et al., 1999). Ramalhete is adjacent to a UWWT plant that discharges organic matter (Mudge and Bebianno, 1997), which increases during the summer months with the influx of tourists to the area. In addition, the residence time of water at this site of the inner lagoon is greater than at the sites on the outer lagoon (Newton and Mudge, 2003). Other studies have shown that transport mechanisms can concentrate algal biomass at a single location from algal assemblages located at other sites in an estuary or lagoon (Lucas et al., 1999; Monsen et al., 2002).

Clustering analysis shows that there is an oceanic community of microplankton at the Barra that is distinct from the lagoon communities at the Ponte and Ramalhete. Benthic studies of the Ria also point to a distinct lagoonal assemblage in relation to the adjacent Atlantic Ocean (Lock and Mees, 1999). Lagoonal waters frequently have a distinct phytoplanktonic assemblage, compared to the adjacent coastal waters (Sarno et al., 1993). During winter, the Ria is exposed to run-off episodes induced by rainfall (Newton et al., 2003), whereas coastal waters are influenced by upwelling events (Fiúza, 1983) and the warmer currents from Cádiz (Relvas and Barton, 2002). Essentially, the Ria-ocean assemblages are exposed to different physical, trophic and biological conditions that select for distinct biotic communities (Margalef, 1978; Dronkers and Zimmerman, 1982; Reynolds, 2001).

Community analysis groups the microplankton assemblage according to seasonal factors suggesting that the microplankton structure in the lagoon is mainly influenced by variability in seasonal parameters, as opposed to tidal and spatial effects. These are mainly: the physical parameters of temperature, solar radiation, and to a lesser extent salinity; and the chemical parameters, in the form of reduced nitrogen compounds. The more extreme summer conditions support a lower diversity assemblage, probably, because of the higher levels of stress selecting for the fittest life-forms (Hutchinson, 1961; Margalef, 1978). Under the milder environmental conditions of the autumn and spring, the mixed populations exhibit a more diverse community (Connell, 1978). The high diversity and equitability indices continue into winter, due to the decrease of individuals associated with the maintenance of taxa numbers.

4.3. Nutrient enrichment experiments

Over the same period as this current study, there have been short term experiments with nutrient enrichment of nitrogen and phosphorus to estimate how the pelagic microplankton community described in this current study might respond to eutrophic conditions during LW and HW, around the summer solstice in 2001 and 2002, and around the autumn equinox of 2001 (Loureiro et al., 2005b). At the sites within the lagoon, the production and biomass are consistently stimulated by nitrogen during the summer but not during the autumn. In contrast, water entering the oceanic inlet at HW is only stimulated during the autumn.

A microcosm experiment using continuous culture techniques has also been carried out over 7 days during April 2002 using lagoon water collected during LW at the Ponte site (Edwards et al., 2005). After enrichment with nutrients, whereby nitrogen would become the limiting nutrient over time, both production and biomass of the microplankton attained a maximum within four days. In both sets of experiments and, in common with other observations in the literature (Loureiro et al., 2005b, references therein), diatoms are the main community that responds to nutrient enrichment.

4.4. Modelling and the application of monitoring indices for eutrophication

Nobre et al. (2005) have used data for the lagoon from a relational database (Newton et al., 2003) to calibrate and validate EcoWin (Ferreira, 1995), a complex ecological model that simulates physical and biogeochemical state variables for multi-year runs. The water fluxes over the modelling domain have been calculated from the MOHID hydrodynamic model (Silva et al., 2002). The output from the complex research model (EcoWin) has been used to drive ASSETS (Assessment of Estuarine Trophic Status; Bricker et al., 2003), a simple screening model for eutrophication that has been refined from the NEEA approach (United States National Estuarine Eutrophication Assessment; Bricker et al., 1999) that evaluates symptoms of eutrophication such as: increases in chlorophyll *a* and macroalgal biomass; low concentrations of dissolved oxygen;

loss of submerged aquatic vegetation; and development of nuisance or toxic blooms. The data set for the Ria Formosa, including data from this study, achieves a score of “good” from a eutrophication status of five classes ranging from “high” to “bad”. This hybrid approach to eutrophication assessment has been used to predict the response of the lagoon to a range of nutrient loads, as well as investigate scenarios where there is currently no data. An example of this is night-time anoxia in tide pools. Newton and Icely (in press) have also examined what the CSST screening model for eutrophication (Comprehensive Studies Task Team; Tett et al., 2003) would predict for the Ria Formosa. Results suggest that the effects would only be limited in the outer lagoon, but there are possibilities for problems in the inner lagoon, where water exchange is more restricted. An important aspect of this model is the development of biological parameters to assess the “balance of organisms” from the microplankton assemblage. These parameters include Eta (η ; Tett and Wilson, 2000), which estimates the heterotrophic contribution to the total microplankton community, and psi (ψ ; Tett et al., 2003), which estimates the ratio of phytoplankters (flagellates, dinoflagellates and cyanobacteria) that do not require silicate. η is associated with oxygen related processes and ψ to the presence of “undesirable” algae, and, as such, can be used for assessments of eutrophication. η and ψ vary considerably for the Ria Formosa lagoon (Newton and Icely, in press) particularly at Barra and Ponte where the residence time of the water masses is generally less than a day.

ASSETS and CSST are part of a suite of models that have been developed to evaluate trophic conditions in marine areas. Other examples include the new trophic index (TRIX) proposed by Vollenweider et al. (1998), which is based on chl *a*, oxygen saturation, mineral N and total P. The eutrophication risk index (EUTRISK) and the Physically Sensitive Area index (PSA) are indices for eutrophication sensitive areas in European coastal waters (Druson et al., 2002). EUTRISK is based on biomass flux estimated by remote sensing chl *a* maps, and PSA combines the physical factors influencing the primary production on the surface with the oxygen availability in the bottom layer. In 1997, OSPAR (Oslo and Paris Conventions) adopted a Common Procedure for the Identification of the Eutrophication Status of the Maritime Area (OSPAR, 1997) by ascribing to each area, one of three categories: problem, potential problem, or non-problem.

The important point for this current study is that if these models and indices are to be effective, they require data, preferably, a time series of five years or more (EEA, 2001). Also, they must be compared critically, as Newton et al. (2003) have shown that different screening models can produce very different assessments for eutrophication from the same data set.

5. Conclusions

Most of the data obtained for the physical–chemicals conditions (Table 1) are comparable to the historical data for the Ria Formosa (Table 5). There is also a striking difference in

DIN concentrations between the 2001 and 2002 summer solstice that has been attributed to the influence of different coastal water masses. There is an interaction between warmer water supplied by coastal currents from Cadiz, with cooler, nutrient-rich water supplied to the Algarve coast by upwelling events.

This study has provided a baseline of data for phytoplankton in the Ria Formosa. Statistical treatment of the data with PRIMER[®] software has identified microplanktonic assemblages in waters with oceanic origins that are distinct from those in waters with lagoonal origins. In addition, the dominant factor separating the various groups after cluster analysis is the sampling season. Temperature, solar radiation, salinity and reduced forms of nitrogen are the main parameters contributing to these clusters. Although sampling interval of three months is not ideal to establish an annual cycle for phytoplankton in the lagoon, it has been possible to add value to this baseline data through microcosm experiments, which have shown that nitrogen is the principle limiting nutrient in the water column of the lagoon, and that diatoms are the principle microorganisms that will respond to elevated concentrations of nutrients (Edwards et al., 2005; Loureiro et al., 2005b).

In relation to ‘surveillance’ monitoring of the boundary conditions for the WFD (Water Framework Directive), the sampling interval of three months used in this study has provided adequate data on the physico-chemical quality elements needed for comparison with the historical data. The most developed of the screening models for eutrophication (e.g. CSTT, ASSETS) have used the data on the Ria Formosa to classify the chemical and ecological status of the lagoon as good. However, more detailed sampling, or ‘investigative’ monitoring in terms of the WFD, is necessary to study those sections of the inner lagoon where residence time is much higher (2–3 days, Newton and Mudge, 2003; Mudge pers. obser.) and, also, to establish in more detail the interactions between the lagoon and the adjacent coastal water masses. Investigative monitoring is also necessary to establish the interactions between the atmospheric, pelagic, benthic and ground water domains in the lagoon.

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