Do lagoon physiography and hydrology determine the physico-chemical properties and trophic status of coastal lagoons? A comparative approach.

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Coastal lagoons are very heterogeneous systems covering a wide range of physiographical and hydrological characteristics. The hypothesis of the present investigation was to test physiographical and hydrological characteristics of coastal lagoons affecting their physico-chemical properties and their buffer capacity against nutrient enrichment. We compared data collected during a whole annual cycle in six coastal lagoons which were representative of the different lagoon types proposed by Kjerfve (1986) and were subjected to different anthropogenic pressures. The higher exchange of water with sea in the leaky lagoon of Ria Formosa (type 3) reduced the seasonal differences in the physico-chemical variables and increased the buffer capacity against nutrient enrichment when compared to the restricted (type 2) and choked (type 1) lagoon types. The lagoon types also registered important differences regarding nutrient limitation, with types 1 and 2 being P-limited and type 3 being N-limited. The results of such a work, could be applied to other coastal lagoons being the systems studied in the current work representative of transitional water types in order to provide general framework for a rational management and policy strategies of coastal lagoons.

Key words: coastal lagoons, physiographical and hydrological features, nutrient enrichment, eutrophication.
1. Introduction

Coastal lagoons can be broadly defined as natural lentic water bodies distributed along the continental shoreline. Thus, coastal lagoons can be precisely defined as shallow aquatic ecosystems that develop at the interface between coastal terrestrial and marine ecosystems and can be permanently open or intermittently closed off from the adjacent sea by depositional barriers (Kjerfve, 1994; Gönenç and Wolfin, 2005). Water can span the range of salinities from hypersaline to completely fresh depending on the relative strength of the particular drivers of their hydrological balance, such as local precipitation, watershed inflow, evaporation and sea-water intrusion by percolation through, or overtopping of, the sand barrier (Bird, 1994; Smith, 1994). Coastal lagoons can be subdivided into choked, restricted and leaky systems based on the degree of water exchange with the ocean (Kjerfve, 1986). Choked lagoons are characterized by a single entrance channel and a small ratio of entrance channel cross-sectional area to surface area of the lagoon. They are dominated by the hydrologic/riverine cycles; have long residence times; are wind forced; and experience limited short-term marine variability. Leaky lagoons, on the other hand, are characterized by multiple entrance channels and a relatively large ratio of entrance channel cross-sectional area to surface area of the lagoon. They are dominated by marine influence, near-oceanic salinities, strong tidal variability, and occasional significant wave energy. Restricted lagoons represent the middle of the spectrum of lagoons between the choked and leaky extremes.

Coastal lagoons are highly productive ecotones and cover some ecological key roles such as denitrification areas, resting areas for many species of migratory birds and nursery areas for commercial invertebrate and fish species (Alonghi, 1998; Basset et al., 2006). Their historical exploitation by humans for settlement and development makes these regions of restricted exchange vulnerable to eutrophication (Newton and Mudge, 2005). Drivers of eutrophication include human activities such as agriculture (Bell, 1991; Viaroli et al., 2005), aquaculture (Strain and Yeats, 1999; Jones et al., 2001), urbanization and industrialization (Bock et al., 1999; Lee and Arega, 1999; White et al., 2008). Southern European lagoons are particularly vulnerable to the resulting pressures from human activities (Viaroli et al., 2005). In recent years, these human pressures have increased causing a complex suite of both direct as well as indirect changes that cause deterioration of water quality and consequently alteration of the ecological state of the
biological communities. This impacts the coastal ecosystem including aspects on human health (Nixon, 1995; Belzunce et al., 2004), social and economic costs (Cloern, 2001).

Eutrophication is considered one of the most relevant disturbance process caused by human impact on aquatic ecosystems (European Commission, 1991) which system-specific attributes act as a filter to modulate the responses to nutrient enrichment (Cloern, 2001). During the last decade it has become apparent that nutrient concentrations may not be a robust diagnostic variable (Cloern, 2001; Dettmann, 2001). Nutrients are the primary cause but there are many other influencing factors that can help to establish a link between a system’s natural sensitivity, or susceptibility, to eutrophication and the eutrophic symptoms that are observed (Bricker et al., 1999; Bricker et al., 2003). Among these factors, physiographical characteristics of coastal lagoons can modulate and control internal hydrodynamic and exchange with adjacent sea, which in turn are responsible of water retention and flushing (Zaldívar et al., 2008).

The aim of present work was to test if physiographical and hydrological characteristics of coastal lagoons affect their physico-chemical properties and their buffer capacity against nutrient enrichment. For this purpose, six coastal lagoons representative of different morphological types (sensu Kjerfve, 1986) and subjected to different anthropogenic pressures level have been compared.

2. Materials and Methods

2.1. Description of study sites and anthropogenic pressures

This study was carried out in seven European water bodies: the large lagoon of Ria Formosa, located on the southern Portuguese coast in the Northeast Atlantic ecoregion; Lesina and Varano lagoons located on the Southern Adriatic coast of Italy, and three small water bodies, CaL’Arana, Ricarda and Cal Tet, on the Northern Mediterranean coast of Spain in the Mediterranean ecoregion (Figure 1).

The Ria Formosa (RF) is a sheltered, shallow and mesotidal coastal lagoon in the South of Portugal and it is generally well mixed vertically (Newton and Icely, 2006). The system is 55 km long, 6 km at its widest, with an average channel depth of 3.5m, and has an area of 160 km$^2$, of which one third is intertidal. The lagoon has 10,000 ha that includes 5,000 ha of saltmarsh and mud flats, 2,000 ha of sand banks and 1,000 ha of saltpans and aquaculture ponds (Newton et al., 2003). This coastal lagoon is separated from the Atlantic Ocean by several barrier islands and two peninsulas, and
water exchange with oceanic waters is achieved through several inlets. At each tide, there is a 50-75% exchange of water (Loureiro et al., 2006). Tidal range varies from 1.3 m to 2.8 m at neap and spring tides, respectively. Salinity ranges from 13 to 36.5, and temperature from 12 to 27°C (Loureiro et al., 2006; Ferreira et al., 2003). The lagoon is located in an urbanised area surrounded by agricultural land and is, therefore, vulnerable to anthropogenic eutrophication. Only one small freshwater input is permanent throughout the year. All the other freshwater inputs are torrential streams which only flow into the lagoon during episodic precipitation events. As the salinity gradient is insufficient to be considered transitional water, Ria Formosa is categorised as a coastal water (Goela et al., 2009). The lagoon is an important resource in the local region because of the intensive fishing, aquaculture, salt extraction and seasonal tourism activities (Loureiro et al., 2006 and Tett et al., 2003).

Lesina and Varano lagoons (Fig. 1c), located on the Southern Adriatic coast of Italy (Puglia region), are non-tidal transitional water body characterised by shallow waters (0.7-1.5 and 2-5 m, respectively) with an area of 51 and 65 km², respectively. They are both connected to the sea through two inlets. Lesina lagoon shows a hydrological heterogeneity strongly influenced by meteorological conditions, continental inputs and low tidal exchange (Roselli et al., 2009). Numerous watercourses flow into the basin, mainly along its Southern edge, carrying wastewater discharges from aquaculture plants and three municipalities with a total of 30,000 inhabitants, as well as agricultural runoff from 21,000 ha of arable land. The lagoon has potentially low vulnerability to human activities even though eutrophication events have been recorded (Roselli et al., 2009, Vignes et al., 2009). Varano lagoon shows temporal variation and spatial heterogeneity in hydro-chemical parameters probably determined by seasonal pattern and sea-exchange (Roselli, 2008). The catchment area is about 350 km². Main watercourses, located along the South-eastern edge of the basin, flowing wastewater discharges from municipalities with 22,000 inhabitants, as well as agricultural runoff, mostly covered by olive and citrus grove. The economic relevance of Varano lagoon is mostly related to fishing and aquaculture activity. Also, there are underground freshwaters mostly on the Southern edge.

The Llobregat’s river deltaic plain was in its origins a vast wetland formed by the deposition of alluvial material swept along by the Llobregat’s river (Cabello and Ramos, 2007). Most of the natural-formed lagoons were born under the influence of the
river, and had no direct connection with the sea (Planas, 1984). Nowadays, the area is profoundly transformed by human action: the water has been dried-out for construction purposes, the aquifer has been over-exploited, the river has been canalized, and some of these lagoons have disappeared, while some new ones have been created. We focused the study in three coastal lagoons: Ricarda, Cal’Arana and Cal Tet (Fig. 1). Most of the lagoons’ incoming water fluxes are human-regulated nowadays, since its connection with the river has been lost and sea-lagoon exchange is restricted, being often reduced to groundwater percolation (Cañedo et al., in press). The human regulation of these water fluxes derived in sporadic large freshwater releases in the Ricarda and Ca l’Arana lagoon, causing a significant salinity decrease and having significant effects over the aquatic communities (Cañedo-Argüelles and Rieradevall, 2010). Ricarda is a naturally formed lagoon, subjected to artificial freshwater inputs and agricultural runoff. It is shallow (max. depth ¼ 2 m), covering an area of 8.42 ha and it is intermittently connected to the sea through its mouth. The actual lagoon of Ca l’Arana is placed where once there was a natural lagoon. This old lagoon disappeared and was replaced by a quarry basin of 7mof maximum depth and an area of 1 Ha, which is now completely filled with water coming from the superficial aquifer and has important artificial freshwater inputs (Cañedo-Argüelles and Rieradevall, 2010). The most recent created lagoon is Cal Tet, as a compensation measure for the loss of natural habitats in the delta as a consequence of the airport’s and port’s expansion. The lagoon is shallow (maximum depth 1.5 m), comprising an area of 16 ha and is exclusively fed by ground waters coming from the superficial aquifer. The water renewal is therefore very poor, and the evaporation is progressively drying the lagoon driving to the apparition of eutrophication symptoms (Cañedo-Argüelles et al., 2011).

2.2. Sampling design

Ria Formosa - Two sampling stations (Ramalhete and Ponte) were sampled at the east region of the Ria Formosa lagoon between April 2006 and November 2007 at high and low water conditions. In both stations samples were collected each fifteen days during the sampling period. Ponte station, with a sandy-muddy substrate, can suffer influence from effluents coming from nearby golf courses, agricultural runoff, tourism activities and bivalve culture, while Ramalhete, with a muddy substrate and where water exchanges are slower than in Ponte site (Newton and Mudge, 2003), receives effluents of a Urban Waste Water Treatment Plant, and is close to a international airport.
At each station, surface water was collected for chla suspended particulate matter, Dissolved Oxygen (DO) and was measured the surface sea temperature and salinity with a probe (WTW conductivity meter ProfiLine Cond 197i).

Lesina and Varano – Lesina and Varano lagoons were sampled monthly during one year sampling from September 2006 to August 2007. In Lesina lagoon three stations were selected along a trophic and salinity gradient from the western to the eastern part of the basin (Fig. 1c). In Varano lagoon three stations were selected (Fig. 1c). Station 1 is near the sea-exchange canal, Station 2 is located in the middle of the basin which is the maximum depth point (5 m water depth), Station 3 is located along the south-eastern edge where main freshwater inputs flowing into the basin. The stations in both lagoons were selected following the experience acquired during several previous studies (Caroppo, 2000; Manini et al., 2003, Fabbrocini et al., 2005; Roselli et al. 2009). At each station, water temperature, salinity and oxygen saturation were measured with a multiparametric probe (YSI 556 MPS). Replicate water samples were collected for chla and nutrient analyses using a Ruttner bottle.

Llobregat lagoons - Ricarda, Cal’Arana and Cal Tet were sampled monthly from June 2004 to July 2005. One station located in the middle of each water body was monitored. Water temperature, salinity and oxygen saturation were measured with a multiparametric sensor (WTW, multiparameter model 197i). A surface water sample (1.5 L) was collected in each lagoon and preserved at 4 °C for laboratory analysis of nutrients.

2.3. Quantifying anthropogenic pressures

Based upon expert judgment, pressures were quantified for each location and sampling station on a discrete scale (0: absent; 1: low, 2: medium, 3: high and 4: very high); they were then described in Table 2 as partial pressure, total pressure and combined pressure index, following Aubry and Elliott (2006). The total pressure is the sum of the partial pressures, and the pressure index was calculated as the average of the pressure scores. This approach is similar to that of Borja et al. (2011) and Lugoli et al. (2012).

2.4. Methodological procedures for nutrient and chlorophyll a concentration.

Surface water was collected in order to determine chlorophyll a and nutrient concentrations (ammonium-NH₄⁺, nitrite-NO₂⁻, nitrate-NO₃⁻, soluble reactive phosphorus-SRP and soluble reactive silicate-SRSi). For the analyses of dissolved
nutrients and silicate water was filtered through Whatman 0.7 µm GF/F filters. All the analyses were performed following standard methods (Grasshoff et al., 1983; Greenberg et al., 1999). Dissolved inorganic nitrogen concentration was expressed as the sum of the nitrogen forms (DIN = NH$_4^+$ + NO$_2^-$ + NO$_3^-$). The water samples were filtered using filters of porosity 0.45 µm and chlorophyll a pigment extraction took place in acetone. Chlorophyll a concentration was estimated by spectrophotometry following Jeffrey and Humphrey (1975). DO for Ria Formosa was estimated by a standard Winkler titration (Grasshoff et al., 1999).

### 2.5 Statistical analyses

The statistical analyses were aimed to identify the differences in the physico-chemical characteristics of the 3 lagoon types proposed by Kjerfve (1986) basing on the degree of water exchange with the adjacent coastal ocean: choked, restricted and leaky. All the statistical analyses were performed using R (http://www.r-project.org/), which is a free software environment for statistical computing and graphics.

First the significance of the established lagoon types in terms of physico-chemical properties was tested through a partitioning clustering (pam function, CLUSTER package) of the data into k clusters “around medoids”, where k = 3 (number of lagoon types). The pam-algorithm is based on the search for k representative medoids (representative objects whose average dissimilarity to all the objects in the cluster is minimal) among the observations of the dataset (Reynolds et al., 1992). These observations should represent the structure of the data. After finding a set of k medoids, k clusters are constructed by assigning each observation to the nearest medoid. The goal is to find k representative objects, which minimize the sum of the dissimilarities of the observations to their closest representative object. The number of cluster was set to 3 to test if each lagoon type was assigned to a different cluster (i.e. physiographical differences driving to differences in the physico-chemical properties). Classical multidimensional scaling (cmdscale function, STATS package), also known as principal coordinates analysis (Gower, 1966), was used to plot the differences between groups. Multidimensional scaling takes a set of dissimilarities and returns a set of points such that the distances between the points are approximately equal to the dissimilarities (Mardia, 1978). Euclidean distance was used for building the dissimilarity matrix. The differences between lagoon types for each physico-chemical variable were further explored using beanplot analysis (beanplot function, BEANPLOT package). A beanplot is an alternative to the boxplot for visual comparison of univariate data between groups.
(Kampstra, 2008). In a beanplot, the individual observations are shown as small lines in a one-dimensional scatter plot. Next to that, the estimated density of the distributions is visible and the average is shown.

3. Results

The cluster analysis (Figure 2) grouped the samples as follows:

- **Group 1**: 27 samples (44% of the samples contained in that group) of the lagoon type 1 (chocked) and 34 samples (56% of the samples contained in that group) of the lagoon type 2 (restricted).

- **Group 2**: 15 samples (29% of the samples contained in that group) of the lagoon type 1 (chocked), 35 samples (69% of the samples contained in that group) of the lagoon type 2 (restricted) and 1 sample (2% of the samples contained in that group) of the lagoon type 3 (leaky).

- **Group 3**: 3 samples (9% of the samples contained in that group) of the lagoon type 2 (restricted) and 29 sample (91% of the samples contained in that group) of the lagoon type 3 (leaky).

The classification of the samples according to water temperature (warm/ cold months = those in which water temperature was higher/ lower than the annual mean of 18.82°C respectively) allowed for a clear separation between the cluster groups 1 and 2:

- **Group 1**: 55 samples (90% of the samples contained in that group) corresponding to warm months and 6 samples (10% of the samples contained in that group) corresponding to cold months.

- **Group 2**: 8 samples (16% of the samples contained in that group) corresponding to the warm months and 43 samples (84% of the samples contained in that group) corresponding to the cold months.

The first axis of the multidimensional scaling explained a 36.34 % of the total variance in the dissimilarity matrix and was mainly related to lagoon the degree of water exchange with the ocean, distinguishing between the leaky (negative values of axis 1) and the chocked and the restricted (positive values of axis 1) lagoon types. The second axis explained a 25.73 % of the total variance in the dissimilarity matrix and was mainly related to season, distinguishing between the cold (negative values of axis 2) and the warm (positive values of axis 2) months.
Physico-chemical characteristics for each lagoon type are presented in Figure 3.

Annual variations in water temperature were highest in the chocked type (min. = 5.80°C; max. = 30.5°C) and lowest in the leaky type (min. = 14°C; max. = 28.10°C). Conductivity steadily increased from type 1 (mean annual conductivity = 6.27 mS cm\(^{-1}\)) to type 3 (mean annual conductivity = 36.74 mS cm\(^{-1}\)). On the opposite side, chlorophyll a concentrations were highest in the type 1 (mean annual value = 26.32 μg l\(^{-1}\)) and lowest in the type 3 (mean annual value = 2.00 μg l\(^{-1}\)). Soluble reactive silicate registered a strong seasonal pattern in chocked lagoons (min. = 2.30 mol l\(^{-1}\), max. = 147.36 mol l\(^{-1}\)) that was smoothed out while the connection with the sea increased (leaky type: min. = 2.69 mol l\(^{-1}\), max. = 16.11 mol l\(^{-1}\)). Dissolved oxygen registered higher concentrations and lower annual variation in the chocked (mean annual DO = 104.88%) and the restricted (mean annual DO = 109.47%) types than in the leaky type (mean annual DO = 65.99%). Nutrients concentration were clearly highest in the chocked type (mean annual value: NO\(_3^-\) = 23.65 mol l\(^{-1}\), NH\(_4^+\) = 3.64 mol l\(^{-1}\) and SRP = 4.53 mol l\(^{-1}\)), intermediate in the restricted type (mean annual value: NO\(_3^-\) = 11.44 mol l\(^{-1}\), NH\(_4^+\) = 2.59 mol l\(^{-1}\) and SRP = 0.10 mol l\(^{-1}\)) and lowest in the leaky type (mean annual value: NO\(_3^-\) = 2.30 mol l\(^{-1}\), NH\(_4^+\) = 1.47 mol l\(^{-1}\) and SRP = 0.73 mol l\(^{-1}\)). The nitrogen/phosphorous ratios (Figure 4) were highest in the restricted type, intermediate in the chocked type and lowest in the leaky type.

4. Discussion

The findings indicate that physiographical and hydrological characteristics of coastal lagoons affect their physico-chemical properties and their buffer capacity against nutrient enrichment. The higher exchange of water with sea in the leaky lagoon of Ria Formosa (type 3) reduced the seasonal differences in the physico-chemical variables and increased the buffer capacity against nutrient enrichment when compared to the restricted (type 2) and chocked (type 1) lagoon types.

Any particular pressure level, in particular nutrient input will have varying effects in different ecosystems due to varying levels of susceptibility to the nutrient inputs (Bricker et al., 1999). This concept based on water body's dilution and flushing potentials, assumes that a larger portion of the water column is potentially available to dilute nutrient loads in a vertically homogenous water body than in a vertically stratified system. According to Bricker et al., (1999) in stratified systems, nutrients are most often retained in the upper freshwater portion of the water column. For water body which are
generally vertically homogenous, nutrients are assumed to be diluted throughout the entire water column. Moreover, it is assumed that a greater capacity to flush nutrient loads exists for ecosystems that have large tide and freshwater influences. In spite of registering the highest values for the pressure indices (Table 2), Ria Formosa registered the lowest nutrient concentrations. Concordantly, Newton and Mudge (2005) found that Ria Formosa has a low susceptibility to eutrophication, because of the dominance of tidal flushing which flushes the water and nutrients quickly from the basin Type 2 (Lesina and Varano) has also a low sensitivity to development of eutrophic conditions, even with human related nutrient inputs, because freshwater inflow into the basin is generally low and drains from watersheds with relatively low anthropogenic pressure (Roselli et al., 2009). In our case type 1 lagoons, which were smaller, deeper and with low water renewal (Llobregat Delta lagoons), are subjected to vertical stratification (Cañedo-Argüelles and Rieradevall, 2010) and receive highly nutrient-rich waters (Lucena et al., 2002; Cañedo-Argüelles and Rieradevall, 2009), sitting in for a long time sufficient for nutrients to be taken up by algae. Therefore, they could be considered more susceptible to developing eutrophic symptoms.

Our results confirm the importance of water renewal and sea-exchange in the prevention of eutrophication symptoms, as it had been previously reported for several lagoons (Tett et al., 2003; Newton and Mudge, 2005; Mudge et al., 2007). The relative contribution of hydrological factors to hydrodynamic depends on physiographical characteristics of coastal lagoon systems. For example, in macrotidal systems, tides control surface water retention time, while in microtidal systems, tides also play an important role, mainly affecting the dynamics of salinity, suspended particulate matter and nutrients (Zaldivar et al., 2008). In this study (see Figure 2) we registered two levels of organization ruled by two different factors: morphology, differentiating the leak type of lagoons with high water renewal, currents and tidal influence versus the restricted and chocked types, where seasonality was a key factor driving to strong physico-chemical differences that could be related to water stratification, which is an important phenomenon in lagoons with restricted water exchange. Therefore, water renewal and sea-exchange do not seem to be factors with a local influence, but key factors determining the vulnerability of coastal lagoons to eutrophication, although other factors, as i.e. the wind (Canu et al., 2003), P storage in sediments (Gikas et al., 2006) and the presence of macrophythenthos (Medina-Gomez and Herrera-Silveira, 2006) have been identified as a key players in the levels of phytoplankton biomass. The lagoon
types also registered important differences regarding nutrient limitation. Inorganic nutrient concentrations in coastal waters reflect the integrated contribution of atmospheric, freshwater and seawater inputs, biological, biochemical and mechanical processes (Fisher et al., 1992) and nutrient concentration ratios is used as index of the relative importance of N, P as factors limiting primary production (Conley, 1999). Chocked and restricted lagoons were phosphorus limited in accordance with findings from previous studies (Cañedo et al., in press) in which P-limited seems to arise from the combination of different factors. Freshwater inputs that can be richer in nitrogen than in phosphorous (Downing and McCauley, 1992) and low tidal exchange, typical of these Mediterranean lagoons, could favour nitrogen excess and phosphorous depletion because phosphate is promptly used by phytoplankton and/or stored in the sediments.

Larger surface area, inlets width and tidal regime may have led to lowest nutrient and chlorophyll a concentrations for type 3. In fact, the Ria Formosa lagoon is larger than the other systems in the study and it is the only mesotidal lagoon. Ria Formosa is considered to be a well-mixed coastal lagoon, with permanent connection with the sea through several inlets, high hydrodynamics and little influence of freshwater inputs. Therefore, the lagoon benefits from effective exchanges between the system and the ocean, due to the higher water renewal (Newton et al., 2003; Newton and Mudge, 2005) that probably could lead to the N-limited system (Loureiro et al., 2005; Newton and Mudge, 2005).

At the present, WFD requires ‘physicochemical quality elements nutrient concentrations, oxygen concentration and transparency (as well as biological quality elements) in order to assess the ecological status of coastal water bodies using salinity and morphology as the criteria for defining water category. However, as already discussed by McLusky and Elliott (2007), there are some unclear situations, such as the Baltic Sea, which has brackish waters and still is considered within the coastal waters typology and some coastal lagoons as Ria Formosa, which are clearly not open coastal waters but at the same time not measurably influenced by freshwater inputs and still are considered within the coastal waters typology. The distinction between the different categories should be ecologically relevant (Brito et al., 2010). We suggest that management and policy actions affecting coastal lagoons should integrate the morphology of the ecosystem as a key factor determining the lagoons’ buffer capacity against nutrient enrichment and shaping the the biotic environment (Guelorget and Perthuisot, 1992; Barnes, 1994; Frénod and Goubert, 2007).
environmental protection of water bodies are based on the typology of the water system
(European Commission, 2000) for the European Water Framework Directive (WFD)
and on “susceptibility” concept for the National Estuarine Eutrophication Assessment of
the US coastal waters (Bricker et al., 1999). Therefore understanding the effects of
lagoons morphological variability on their physico-chemical properties and integrating
it into ecological assessment tools and management policies is one of the major actual
challenges for the managers and the scientists (Basset and Abbiati, 2004; Basset et al.,
2006; Gaertner-Mazouni and De Wit, in press).
Table 1. Main geomorphological characteristics and human pressures in the watershed of the seven considered coastal lagoons. Salinity: oligohaline (0.5–5 psu); mesohaline (5–18 psu); polyhaline (18–30 psu); euhaline (>30 psu).

Table 2. Pressures at each location and sampling station (see Fig. 1), and pressure index, calculated as average of individual pressure scores (Aubry and Elliott, 2006). Scores: 0 – absent; 1 – low pressure; 2 – moderate pressure; 3 – high pressure; 4 – very high pressure.

Figure 1: Aerial photographs of the study sites. From left to right: Ria Formosa, Ricarda, Cal Tet, Cal'Arana, Lesina and Varano lagoons. Sampling points are marked with a white dot.

Figure 2. Multidimensional scaling of the samples using Euclidean distance. The groups resulting from the partitioning clustering (k = 3) are marked with different colors (group 1 = red, group 2 = green, group 3 = blue). The results from the classification of the samples into lagoon types (type 1 = chocked, type 2 = restricted, type 3 = leaky) and according to water temperature (warm/ cold months = those in which water temperature was higher/ lower than the annual mean of 18.82ºC respectively) are shown. N = number of samples. % = percentage of samples from the total of samples assigned to that group.

Figure 3. Bean plots of the different physic-chemical variables for each lagoon type (type 1 = chocked, type 2 = restricted, type 3 = leaky). SR = soluble reactive.

Figure 4. Bean plot of the nitrogen (measured as dissolved inorganic nitrogen)/ phosphorous (measured as soluble reactive phosphorous) for each lagoon type (type 1 = chocked, type 2 = restricted, type 3 = leaky).
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<table>
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<th>Lagoon</th>
<th>Country</th>
<th>Latitude N</th>
<th>Longitude</th>
<th>Surface area (km²)</th>
<th>Mean depth (m)</th>
<th>Maximum width (km)</th>
<th>Maximum depth (m)</th>
<th>Total inlets width (m)</th>
<th>Tidal regime</th>
<th>Salinity</th>
<th>Connection to the sea</th>
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<td>Ria Formosa (RF)</td>
<td>Portugal</td>
<td>36°58' to 37°03'</td>
<td>8°02' to 7°32'W</td>
<td>160</td>
<td>1.5</td>
<td>6</td>
<td>6</td>
<td>4220</td>
<td>mesotidal</td>
<td>euhaline</td>
<td>Permanent (6 inlets)</td>
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<td>41°53' to 41°54'</td>
<td>15°40' to 15°48'</td>
<td>65</td>
<td>3.5</td>
<td>7</td>
<td>5</td>
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<td>polyhaline</td>
<td>Permanent (2 inlets)</td>
</tr>
<tr>
<td>Lesina (LE)</td>
<td>Italy</td>
<td>41°53' to 41°55'</td>
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<tr>
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Table 1.
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Table 2.
Figure 1.
Figure 2.
Figure 3.
Figure 4.