1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

40

41

42

43

44

45

46

47

48

49

50

51

52

53

54

55

56

57

58

59

60

61

62

63

64

65

TEMPORAL AND DIEL CYCLING OF NUTRIENTS IN A BARRIER-LAGOON COMPLEX:
IMPLICATIONS FOR PHYTOPLANKTON ABUNDANCE AND COMPOSITION

ANTONIO COBELO-GARCÍA^{1,*}, PATRICIA BERNÁRDEZ¹, MANUEL LEIRA², DANIEL E. LÓPEZ-SÁNCHEZ¹, JUAN SANTOS-ECHEANDÍA¹, RICARDO PREGO¹, MARTA PÉREZ-ARLUCEA³

¹GRUPO DE BIOXEOQUÍMICA MARIÑA. INSITUTO DE INVESTIGACIÓNS MARIÑAS DE VIGO (CSIC). 36208 VIGO, SPAIN

²FACULTADE DE CIENCIAS. UNIVERSIDADE DE A CORUÑA. A CORUÑA, SPAIN

³DEPARTAMENTO DE XEOCIENCIAS MARIÑAS E ORDENACIÓN DO TERRITORIO. UNIVERSIDADE DE VIGO. 36310 VIGO, SPAIN

*Corresponding author
e-mail: acobelo@iim.csic.es

ABSTRACT

The cycling of nutrients (silicate, nitrate, ammonium and phosphate) in a quasi-pristine barrier-lagoon complex (Louro Lagoon, NW Iberian Peninsula) was studied both in a diel and temporal timescale covering different seasonal conditions. Hydrographical and meteorological conditions exert a major control on the nutrient cycling in the lagoon. From late autumn to early spring the lagoon is characterized by oxic conditions due to significant freshwater inputs and sporadic communication with the sea. In summer, elevated primary production coupled with water stagnancy leads to bottom waters hypoxia and marked diel variation of pH, oxygen and redox potentials. Diel variation of nutrients was only evident when mixing of surface and bottom waters during the night was observed.

Temporal changes in nutrients concentrations and their relative abundance were found to induce a clear shift in the phytoplankton composition. In winter, during silicate and nitrate abundance and low phosphate, diatoms predominate. In summer, under hypoxic conditions, sediments take control on the supply of nutrients leading to increased phosphate availability relative to nitrate/ammonium or silicate. Diatoms are then replaced during the summer blooms – linked to low atomic N:P ratios (typically <2) – by flagellates and green algae with minor contributions of cyanophytes and dinoflagellates.

Keywords: Coastal lagoons, Stagnant water, Nutrient cycles, Phytoplankton composition, NW Iberian Peninsula (Galicia, Muros Ria)

1. INTRODUCTION

Coastal lagoons constitute ecosystems of ecologic, economic and social value and are especially sensitive to both anthropogenic and natural disturbances (Perilla et al., 2012). These environments are highly dynamic and controlled by physical processes, and subject to frequent environmental fluctuations (Pérez-Ruzafa et al. 2005) and the degree of isolation from marine waters (López, 2003). The vulnerability of these systems is greater in the present context of global change, where the sea-level rise, intensification of storms, alterations in the tidal regimes or changes in the freshwater inputs have a significant impact in their functioning. The effect of these changes on nutrient dynamics and phytoplankton communities in coastal lagoon ecosystems (e.g. Pereira et al., 2010; Deborde et al. 2008; Pérez-Ruzafa et al. 2005; Lillebø et al., 2004) are therefore valuable in the present environmental scenario.

Eutrophication and high biological productivity are common characteristic of most coastal lagoons, due to the coupling of several processes which include: (i) elevated inputs of nutrients due to land runoff; (ii) shallowness, allowing light penetration in the whole water column and high exchange between sediments and water column; and (iii) partial isolation from the sea (Deborde et al. 2008). Factors affecting the nutrient cycling in coastal lagoons on a temporal timescale have been extensively characterized for a number different systems (e.g. Hung and Kuo 2002; Souza et al. 2003), showing that nutrient regeneration in the water column and sediments is a key factor enhancing phytoplankton production (Collos et al., 2003; López, 2003). These studies, however, generally rely on data obtained from samples taken during the day and may, at certain conditions, overlook important processes that occur at night (Pereira et al. 2010; Nimick et al. 2011). These include low oxygen and pH values at night compared with the light hours, as well as the release of nutrients due to the degradation of benthic organic matter (Escaravage 1990) and may lead to eutrophication phenomena (Middelburg and Levin 2009). It appears, therefore, that the processes coupled to the light-dark cycle possess a significant control on the nutrients cycling in coastal lagoons.

The present study focuses on the nutrients cycling in a barrier-lagoon complex (Louro Lagoon, NW Iberian Peninsula) both in a diel and temporal timescale. Results will be discussed regarding their implications for phytoplankton abundance and composition.

2. MATERIAL AND METHODS

2.1 Study Site

The Louro Lagoon (Muros Ria, NW Iberian Peninsula; Figure 1) is a quasi-pristine coastal lagoon belonging to the Galician environmentally protected coastal areas network constituting an important habitat for birds. It consists of a shallow water body subject to marked water

1 fluctuations, with a permanently flooded inner part and a peripheral area which is exposed in
2 summer and during sudden outflow events by the inlet. Typical water depth in the inner area
3 during summer is around 0.5 m, whereas in rainy winter conditions water elevation may
4 exceed 2 m.
5

6 The main freshwater input comes from a small stream (3.2 km² catchment area) which usually
7 becomes dry during summer. The lagoon is separated from the sea by well-developed
8 vegetated dunes, and communication with the sea is ephemeral and only occurs under special
9 circumstances. These include: (i) spring tides and south-southwest wind-driven storms leading
10 to inlet opening and leaking through storm corridors; (ii) after prolonged periods of rainfall
11 when the water elevation in the lagoon is higher than the spring high tide, the inlet is opened
12 allowing a sudden outflow. After inlet opening, tidal water enters the lagoon freely for a few
13 days until the channel is again sealed. During summer, water stagnation due to no
14 communication with the sea coupled with null freshwater input and elevated rates of
15 evaporation may lead to hypersaline conditions. A complete description of the water dynamics
16 in the system may be found in Pérez-Arlucea et al. (2011).
17
18
19
20
21
22
23
24
25

26 **2.2 Sampling and Analytical Methods**

27 Seven sampling campaigns were carried out from 2009 (July, September and November) to
28 2010 (January, April, June and September). Samples for nutrients and auxiliary parameters
29 were taken both in surface and bottom waters (aprox. 5 cm below the surface and above the
30 bottom) at 4-hour intervals covering a complete diel cycle. Meteorological conditions (solar
31 irradiance, air temperature, precipitations) along with the water depth at the sampling point
32 (SP in Figure 1) obtained from a pressure transducer (Seabird SBE39 and AQUAlogger 520 PT;
33 Pérez-Arlucea et al. 2011) during the sampling period are shown in Figure 2.
34
35
36
37
38
39

40 Water samples were collected using an all-Teflon® diaphragm pump (Almatec A15TTT) driven
41 using compressed air. A 200 µm nylon mesh was attached to the outlet of the pump in order to
42 remove plant debris and zooplankton. Temperature, pH, salinity and redox potential (ORP)
43 were measured in-situ using a calibrated multiparametric probes (Mettler Toledo SevenGo and
44 WTW Multiline P4). Samples for nitrate, ammonium and phosphate analysis were collected in
45 30-mL LDPE bottles and frozen until analysis, whereas for silicate 10-mL polycarbonate tubes
46 were employed and kept refrigerated (4 °C) to avoid orthosilicate polymerization that may
47 occur in frozen samples (Kobayashi, 1966). Nutrients were analyzed using an Integral Futura
48 autoanalyzer system (Alliance Instruments) according to standard colorimetric methods
49 (Hansen and Koroleff, 1999). The accuracy of the analytical procedure was assessed by the
50 analysis of certified reference materials: MOOS-1 (seawater nutrients; NRC, Canada), obtaining
51 good agreement with the certified values. The precision as relative standard deviation (RSD)
52
53
54
55
56
57
58
59
60
61
62
63
64
65

was always less than 5%. Detection limits, expressed as three times the standard deviation of 10 replicate measurements of reagent blanks, were: 0.14 μM for nitrate, 0.01 μM for ammonium, 0.08 μM for phosphate and 0.14 μM for silicate.

Dissolved oxygen concentrations were measured by the Winkler titration method to calculate saturation percentages (Aminot 1983). For the determination of chlorophyll-a, sample aliquots were filtered through pre-combusted GF/F membranes (Whatman); chlorophyll *a* was then extracted in 90% acetone and determined spectrofluorimetrically (Neveux and Panouse, 1987). Two water samples (100 mL) for phytoplankton identification per sampling campaign were collected in surface and bottom waters at around 12:00 am and immediately preserved with Lugol's solution. After homogenizing the samples, subsamples were allowed to settle on 10-mL sedimentation chambers, according to the method of Utermöhl (1958). Phytoplankton cell were counted by the Utermöhl technique in an Olympus IX70 light inverted microscope, at 400-magnification. Phytoplankton identification was based mainly on Bourrelly (1966, 1968 and 1970) and Tomas (1996).

3. RESULTS

3.1 Temporal nutrients cycling

During the 7 sampling dates, the stream was dry in September '09 and '10. Average pH and ORP were 6.2 ± 0.2 and 360 ± 30 mV (vs. SHE), whereas for nutrients values of (in μM) 100 ± 36 (silicate), 28 ± 11 (nitrate), 2.4 ± 0.7 (ammonium) and 0.14 ± 0.02 (phosphate) were obtained.

In the lagoon, lower pH values in surface waters were found during the rainy season compared to summer (Figure 3); bottom waters followed a similar pattern with the exception of July'09 due anoxic conditions (see below). Salinities less than 10 were recorded from July 2009 to April 2010, but elevated salinities were observed in June and especially September 2010 as a consequence of a prolonged stagnant period and elevated rates of evaporation. Stratification of the water column was observed only during the periods of high precipitations and water depth.

Average oxygen saturation in surface waters was in the range of 60-80%, although pronounced day-night variations were observed during the summer periods (see section 3.2). Bottom oxygen was generally lower, especially in July 2009 when anoxia was present (Figure 4). As expected, redox potentials follow a similar trend as oxygen with lower values in summer and in bottom waters. On November 2009, surface waters showed similar oxygen/redox potential than in winter and spring conditions; however, bottom waters still presented low values indicating a slower transition from the dry to the rainy season.

Table 1 shows the Pearson correlation matrix for nutrients, chlorophyll *a*, and environmental parameters for all the sampling dates with the exception of the September 2010 extreme stagnant low-waters and hypersaline conditions. Maximum nitrate and silicate, which are highly correlated (Table 1), were found during the rainy periods (November to April) due to higher freshwater inputs (Figure 5); the only exceptions were (i) nitrate in bottom waters in November due to low oxygen/redox potential in agreement with the concurrent peak of ammonium; and especially (ii) the maximum silicate values in September 2010, not linked to freshwater inputs but due to sediment organic matter remineralization, which is also observed, though to a lower extent, in July 2009. Maximum phosphate concentrations were found in summer (Figure 5) linked to the minimum oxygen concentrations as evidenced by their significant inverse correlation (Table 1). Release of nutrients – especially phosphate – from sediments during hypoxic conditions due to the reduction of Fe(III) oxyhydroxides is well documented (e.g. Rozan et al. 2002). A similar negative correlation with oxygen is also observed for ammonium (Table), though its temporal trend is not as evident as that of phosphate (Figure 5).

The temporal chlorophyll *a* trend shows maximum values during summer conditions (Figure 5), being strongly correlated with ammonium and especially phosphate (Table 1). Suspended material (SPM) is dominated by autochthonous biogenic ‘particles’ as depicted from its close relationship with chlorophyll *a* (Table 1)

3.2 Diel nutrients cycling

Data shown in Figure 6 correspond to surface diel variations in summer (September 2009), winter (January 2010) and spring (April 2010). Differences in surface water temperature between the night and day were highest during summer – up to 15°C in September 2009 – and lowest in winter – around 6°C in January 2010 (Figure 6). Also, pH showed a marked diel trend, with maximum values around dusk and minimum at dawn. These variations, controlled by the CO₂ consumption during the light hours due to photosynthesis and release at night due to respiration, are normally higher in summer when biological productivity is highest (Nimick et al. 2011). Accordingly, the amplitude of diel pH cycle ranged from 0.5 in winter to about 1.1 in summer. In the period of November to June, no evident diel trends in O₂ saturation/ORP were observed. During the periods of high productivity and stagnant waters in summer, conditions move from oxic conditions during the light hours to hypoxic (defined as <2 mg O₂ L⁻¹; Middelburg and Levin 2009) conditions at night explaining the elevated phosphate recorded.

A peak of salinity at night in surface waters was generally observed during sampling campaigns when stratification was present (see winter and spring trends, Figure 6); this was not found, however, in bottom waters indicating that this night increase at surface was probably due to

1 mixing with bottom waters and is confirmed by the low values of parameters such as nitrate
2 and silicate. Also, in April 2010, an input of ammonium and phosphate from bottom waters
3 was found, which is concurrent with a peak of chlorophyll *a*. Phytoplankton growth seems to
4 be closely linked to the phosphate inputs to the water column (peaks of chlorophyll *a* appear
5 at maximum phosphate concentrations – see Figure 6); this is especially evident for bottom
6 waters (Figure 7). Phosphate release from sediments due to hypoxic/anoxic conditions is well
7 known to favor phytoplankton blooms (Ma et al. 2006), and results presented here
8 demonstrate that this occurs in a short timescale.
9

10 **3.3 Phytoplankton abundances**

11 Microscopic analysis was used to identify the most abundant phytoplankton taxa in the lagoon.
12 The phytoplankton community composition was very similar in the surface and bottom
13 samples although it presented a high seasonal fluctuation (Figure 8). On average, green algae
14 (74%) and flagellates (16%) were the most important groups. The relative contribution of
15 green algae was 85% and 100% of the bottom sample phytoplankton community in November
16 2009 (97% *Carteria* sp.) and September 2010 (100% *Chlamydomonas* sp.) respectively, while it
17 reached 58% of the surface sample in November 2009 (60% *Aphanothece* sp. and 32% *Carteria*
18 sp.) and 98% in September 2010 (100% *Chlamydomonas* sp.). Green algae, mostly
19 *Monoraphidium contortum* (80% and 63%), peaked again on July 2009, representing 72% and
20 42% of the phytoplankton community in the bottom and surface samples respectively.
21

22 Flagellates dominated the phytoplankton community in September 2009 both in the surface
23 (45% *Euglena viridis* and 35% *Chroomonas acuta*) and bottom samples (44% *Euglena viridis*
24 and 37% *Cryptomonas* sp.), representing 80% and 79% of the total community. Flagellates
25 dominated again in surface waters in June 2010 (75% *Chroomonas acuta*), although were
26 absent from the phytoplankton bottom assemblage, where dinoflagellates represented the
27 major group (96% *Gymnodinium* sp.). Diatoms were found in almost all samples and
28 dominated the phytoplankton community from January to April (82-100%) in both surface and
29 bottom samples. Different diatom species were present in surface (36% *Cymbella* sp., 14%
30 *Amphora* sp., 14% *Navicula* sp.) and bottom (25% *Entomoneis* sp., 22% *Haslea crucigera*, 11%
31 *Achnanthes lanceolata*, 11% *Navicula* sp.) waters in January. In April, however, the diatom
32 species distribution was homogeneous in the water column, with *Fragilaria* sp. and *Navicula*
33 sp. as the dominant diatoms (60-70%) in surface and bottom waters.
34

35 **4. DISCUSSION AND CONCLUSIONS**

36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 One of the main factors controlling the species composition of the phytoplankton and the
2 development of blooms is the relative abundance of the major nutrient elements (Anderson et
3 al. 2002). The composition of the nutrient pool and their relative abundance in the Louro
4 Lagoon appears to be strongly affected on a seasonal timescale which results in a shift of the
5 phytoplankton species present in the water column. Accordingly, maximum values of nitrate
6 and silicate (and minimum phosphate) were recorded during periods of significant freshwater
7 input to the lagoon (November to April) favoring the increase in diatoms, which dominate the
8 phytoplankton composition in January and April (Figure 8). In summer, under hypoxic
9 conditions and stagnant waters, sediments take control on the supply of nutrients to the water
10 column and their relative composition, and diatoms are then replaced by flagellates and green
11 algae with minor contributions of cyanophytes and dinoflagellates.

12 Typical values of atomic N:P ratios for aquatic plants roughly range from about 10 to 45
13 (Duarte 1992) whereas the generalized Redfield ratio is 16. Blooms occurring when these
14 ratios of nutrient availability are altered have been explained by the nutrient ratio hypothesis,
15 which argues that the selection of phytoplankton species is linked with the relative availability
16 of specific nutrients (Anderson et al. 2002). Our data indicates that the summer phytoplankton
17 blooms due to flagellates and green algae (with the exception of bottom waters in July 2009,
18 where the N:P is close to the Redfield ratio) are associated with low N:P ratios (typically <2;
19 Figure 9). In winter, however, when biomass production decreases and diatoms dominate,
20 these ratios are generally above 50. These results are in agreement with previous studies (e.g.
21 Rozan et al. 2002) which found that the release of phosphate and ammonium from sediments
22 under hypoxic/anoxic conditions may lead to eutrophication phenomena and changes in the
23 phytoplankton composition due to the increase in the availability of N or P relative to silicate
24 or changes in the N:P ratios (Anderson et al. 2002; Ma et al. 2006). The absence of diatoms in
25 phosphate-rich summer conditions even when silicate is abundant due to sediment
26 remineralization (bottom waters of July'09 and surface and bottom waters of September'10)
27 further evidences the phosphate control on phytoplankton composition.

28 Results presented in this study provide a good example of the impact of nutrient cycling on
29 phytoplankton abundance and composition in coastal lagoons. The temporal and diel cycling of
30 nutrients in the Louro Lagoon, a quasi-pristine barrier-lagoon complex, is strongly controlled
31 by hydrographical and meteorological conditions. The fragile equilibrium between the winter
32 oxic and nitrate/silicate rich waters and the summer hypoxic and phosphate/ammonium
33 dominance may be broken if climatic (e.g. prolonged dry periods, elevation of temperatures)
34 or anthropogenic (e.g. inputs of nutrients from agricultural activities) are altered. In such a
35 scenario, hypoxic conditions may be easily extended beyond the summer period and the
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 capability of the lagoon to seasonally recover to oxic winter conditions would be diminished,
2 with an obvious impact on the phytoplankton composition and therefore changes in the
3 communities at higher trophic levels (Anderson et al. 2002).
4
5
6

7 5. ACKNOWLEDGMENTS

8 This work was funded by the Galician Government (*Xunta de Galicia*) through the project ref.
9 08MDS036000PR. The C.S.I.C., under the program JAE-PreDoc (*Junta para la Ampliación de*
10 *Estudios*) co-funded by the *Fondo Social Europeo* (FSE), is greatly acknowledged for the
11 predoctoral fellowship to D.E. López-Sánchez. We are grateful to Prodemar (Stolt Sea Farm,
12 S.A.) for allowing access to their labs during the sampling campaigns. We thank P. Cambeiro, C.
13 Almécija, A. Rodríguez, and P. Neira (IIM-CSIC) for assistance during the sampling campaigns
14 and J. Lorenzo (IEO) for chlorophyll *a* analysis.
15
16
17
18
19
20
21
22

23 6. REFERENCES

- 24 Aminot, A., 1983. Dosage de l'oxygene dissous. In: Aminot, A., Chaussepied, M. (Eds.), Manuel
25 des Analyses Chimiques en Milieu Marin. CNEXO, Brest, pp. 75–92.
26
27 Anderson, D.M., Glibert, P.M., Burkholder, J.M., 2002. Harmful algal blooms and
28 eutrophication: nutrient sources, composition, and consequences. *Estuaries* 25, 704-726.
29
30 Bourrelly P., 1966. Les Algues d'eau douce. Tome I: algues vertes. N. Boube'e & Co., Paris.
31
32 Bourrelly P., 1968. Les Algues d'eau douce. Tome II, algues jaunes et brunes. N. Boube'e & Co.,
33 Paris.
34
35 Bourrelly P., 1970. Les Algues d'eau douce. Tome III, algues bleues et rouges. N. Boube'e & Co.,
36 Paris.
37
38 Collos, Y., Vaquer, A., Bibent, B., Souchu, P., Slawyk, G., Garcia, N., 2003. Response of coastal
39 phytoplankton to ammonium and nitrate pulses: seasonal variations of nitrogen uptake and
40 regeneration. *Aquatic Ecology* 37, 227-236.
41
42 Deborde, J., Anschutz, P., Auby, I., Glé, C., Commarieu, M.-V., Maurer, D., Lecroart, P., Abril,
43 G., 2008. Role of tidal pumping on nutrient cycling in a temperate lagoon (Arcachon Bay,
44 France). *Marine Chemistry* 109, 98-114.
45
46 Duarte, C.M., 1992. Nutrient concentration of aquatic plants: patterns across species.
47 *Limnology and Oceanography* 37, 882-889.
48
49 Escaravage, V., 1990. Daily cycles of dissolved oxygen and nutrient content in a shallow
50 fishpond: the impact of water renewal. *Hydrobiologia* 207, 131-136.
51
52 Hansen, H.P., Koroleff, F., 1999. Determination of nutrients. In: Grasshoff, K., Kremling, K.,
53 Ehrhardt, M. (Eds.), *Methods of Seawater Analysis*. Wiley-VCH Verlag, Weinheim, pp. 159–226.
54
55
56
57
58
59
60
61
62
63
64
65

1 Hung, J.-J., Kuo, F., 2002. Temporal variability of carbon and nutrient budgets from a tropical
2 lagoon in Chiku, Southwestern Taiwan. *Estuarine, Coastal and Shelf Science* 54, 887-900.

3 Kobayashi, J., 1966. Silica in freshwater and estuaries, In: Golterman, H.L., Clymo, R.S. (Eds.),
4 Chemical Environment in the Aquatic Habitat. Biosphere Programme Symposium, Amsterdam,
5 pp. 41–55.

6
7
8 Lillebø, A.I., Neto, J.M., Flindt, M.R., Marques, J.C., Pardal, M.A., 2004. Phosphorous dynamics
9 in a temperate intertidal estuary. *Estuarine, Coastal and Shelf Science* 61, 101-109.

10
11 López, P., 2003. Effects of changes in water salinity on ammonium, calcium, dissolved inorganic
12 carbon and influence on water/sediment dynamics. *Estuarine, Coastal and Shelf Science* 56,
13 943-956.

14
15
16 Ma, S., Whereat, E.B., Luther, G.W., 2006. Shift of algal community structure in dead end
17 lagoons of the Delaware Inland Bays during seasonal anoxia. *Aquatic Microbial Ecology* 44,
18 279-290.

19
20
21
22 McCarthy, J.J., Taylor, W.R., Taft, J.L., 1977. Nitrogenous nutrition of the plankton in the
23 Chesapeake Bay. I. Nutrient availability and phytoplankton preferences. *Limnology and*
24 *Oceanography* 22, 996-1011.

25
26
27 Middelburg, J.J., Levin, L.A., 2009. Coastal hypoxia and sediment biogeochemistry.
28 *Biogeosciences* 6, 1273-1293.

29
30
31 Neveux, J., Panouse, M., 1987. Spectrofluorometric determination of chlorophylls and
32 pheophytins. *Archiv für Hydrobiologie* 109, 567-581.

33
34
35 Nimick, D.A., Gammons, C.H., Parker, S.R., 2011. Diel biogeochemical processes and their
36 effect on the aqueous chemistry of streams: a review. *Chemical Geology* 283, 3-17.

37
38
39 Pereira, P., de Pablo, H., Carvalho, S., Vale, C., Pacheco, M., 2010. Daily availability of nutrients
40 and metals in a eutrophic meso-tidal coastal lagoon (Óbidos lagoon, Portugal). *Marine*
41 *Pollution Bulletin* 60, 1868-1872.

42
43
44 Pérez-Arlucea, M., Almécija, C., González-Villanueva, R., Alejo, I., 2011. Water dynamics in a
45 barrier-lagoon system: controlling factors. *Journal of Coastal Research* SI64, 15-19.

46
47
48 Pérez-Ruzafa, A., Fernández, A.I., Marcos, C., Gilabert, J., Quispe, J.I., García-Charton, J.A.,
49 2005. Spatial and temporal variations of hydrological conditions, nutrients and chlorophyll a in
50 a Mediterranean coastal lagoon (Mar Menor, Spain). *Hydrobiologia* 550, 11-27.

51
52
53 Rozan, T.F., Taillefert, M., Trouwborst, R.E., Glazer, B.T., Ma, S., Herzage, J., Valdes, L.M., Price,
54 K.S., Luther, G.W., 2002. Iron-sulfur-phosphorus cycling in the sediments of a shallow coastal
55 bay: Implications for sediment nutrient release and benthic macroalgal blooms. *Limnology &*
56 *Oceanography* 47, 1346-1354.

57
58
59
60
61
62
63
64
65

1 Souza, M.F.L., Kjerfve, Knoppers, B., Landim de Souza, W.F., Damasceno, R.N., 2003. Nutrient
2 budgets and trophic state in a hypersaline coastal lagoon: Lagoa de Araruama, Brazil.
3 Estuarine, Coastal and Shelf Science 57, 843-858.
4

5 Tomas, C.R., 1997. Identifying marine phytoplankton. Academic Press: San Diego
6

7 Perilla, O.L.U., Gómez A.G., Gómez A.G., Díaz, C.A., Cortezón, J.A.R., 2012. Methodology to
8 assess sustainable management of water resources in coastal lagoons with agricultural uses:
9 An application to the Albufera lagoon of Valencia (Eastern Spain). Ecological Indicators 13, 129-
10 143.
11
12

13 Utermöl H., 1958. Zur vervollkommnung der quantitativen phytoplankton-methodik.
14 Mitteilungen der Internationalen Vereinigung für Theoretischen und Angewandten. Limnologie
15 9, 1-38.
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

FIGURE CAPTIONS

Figure 1. Map of the Louro Lagoon including a digital elevation model based on a Laser Scanner image over-imposed to an ortophotograph (Pérez-Arlucea et al. 2011). The sampling point (SP) is indicated by a white dot.

Figure 2. Upper figure: Meteorological conditions: precipitation (grey bars), air temperature (solid line) and solar irradiance (grey dots) during the sampling period. Sampling dates are indicated by closed triangles. Lower figure: water depth of the lagoon at the sampling point. Arrows indicate inlet opening events.

Figure 3. Seasonal trends of pH, temperature and salinity in surface (upper panel) and bottom (lower panel) waters. Whisker plots represent data for a complete diel cycle.

Figure 4. Seasonal trends of redox potential (ORP), oxygen saturation and suspended particulate matter (0.2-20 μm) in surface (upper panel) and bottom (lower panel) waters. Whisker plots represent data for a complete diel cycle.

Figure 5. Seasonal trends of chlorophyll *a*, silicate, nitrate, ammonium and phosphate in surface (upper panel) and bottom (lower panel) waters. Whisker plots represent data for a complete diel cycle.

Figure 6. Diel variations of surface pH, temperature, oxygen saturation, ORP, chlorophyll *a*, salinity, silicate, nitrate, ammonium and phosphate for selected sampling dates of summer (September 2009), winter (January 2010) and spring (April 2010).

Figure 7. Diel trends of chlorophyll *a* (filled circles) and phosphate (empty circles) in bottom waters from September 2009 to September 2010

Figure 8. Phytoplankton abundances (in number of cells per mL), grouped in five major groups (cyanophytes, diatoms, dinoflagellates, flagellates, and green algae), in surface (a) and bottom (b) waters. See text for a more detailed composition.

Figure 9. Chlorophyll *a* abundance vs. atomic N:P ratios for surface (a) and bottom (b) waters. Inserts represent expanded view at low N:P ratios.

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Figure(s)

Table 1. Pearson correlation matrix ($n=84$) for the nutrients, chlorophyll *a*, suspended particulate matter (SPM) and other environmental parameters (O₂ saturation, pH, temperature, and salinity) using the data of obtained during all the sampling dates except Sept10 (see text for further information)

	Nitrate	Ammonium	Phosphate	Silicate	N/P	Chl <i>a</i>	SPM	O ₂	pH	T	S
Nitrate	1	-0.204	-0.338***	0.568***	0.212	-0.344***	-0.371***	0.267**	-0.445***	-0.723***	-0.450***
Ammonium		1	0.777***	0.099	0.070	0.744***	0.143	-0.593***	-0.352***	0.084	-0.141
Phosphate			1	-0.206	0.302***	0.827***	0.567***	-0.511***	-0.039	0.319***	-0.236*
Silicate				1	0.486***	-0.112	-0.327***	-0.041	-0.705***	-0.575***	-0.512***
N/P					1	-0.237*	-0.267**	-0.138	-0.571***	-0.401***	-0.105
Chl <i>a</i>						1	0.503***	-0.490***	-0.057	0.287***	-0.201
SPM							1	-0.206	0.161	0.381***	-0.110
O ₂								1	0.351***	0.123	0.157
pH									1	0.636***	0.295***
T										1	0.495***
S											1

* $p<0.05$; ** $p<0.02$; *** $p<0.01$