Comparing the biogeochemical functioning of two arid subtropical coastal lagoons: the effect of wastewater discharges

Julio Medina-Galván, Carmen Cristina Osuna-Martínez, Gustavo Padilla-Arredondo, Martín Gabriel Frías-Espericueta, Ramón Héctor Barraza-Guardado and José Alfredo Arreola-Lizárraga

*Facultad de Ciencias del Mar, Universidad Autónoma de Sílao, Mazatlán, México; 4Programa de Planeación Ambiental y Conservación, Centro de Investigaciones Biológicas del Noroeste, S.C., Guaymas, México; 5Departamento de Investigaciones Científicas y Tecnológicas de la Universidad de Sonora, Hermosillo, México

**ABSTRACT**

Nutrient flux, net metabolism, and N₂ fixation and denitrification processes were estimated and compared in two semi-arid subtropical coastal lagoons in the Gulf of California: El Soldado (ES), where no wastewater is discharged, and El Rancho (ER), where shrimp farm effluents are regularly discharged. Biogeochemical processes were evaluated with the LOICZ model. Flushing time was <2 days in both systems. Nutrient fluxes were higher in ER than in ES and both systems acted as nutrient sinks for most of the year. ER showed a larger nutrient flow rate in the summer and autumn due to the input of shrimp-farm effluents. Nitrogen fluxes increased in both ER and ES in the winter in response to the increased nutrient supply from coastal upwellings. ER and ES both showed autotrophic metabolism and N₂ fixation in the spring, autumn, and winter, but heterotrophic metabolism and denitrification in the summer. Denitrification dominated in ER (~2.21 mmol m⁻² day⁻¹) and values were higher than those estimated in ES (~0.45 mmol m⁻² day⁻¹). The comparative analysis between ES and ER evidenced the significant changes in its biogeochemical performance caused by the input of anthropogenic nutrients, and can orient the environmental management of coastal lagoons.

**Introduction**

Biogeochemical cycles comprise numerous biological, chemical, and geological processes that interact among themselves and determine the flow of elements between sources and sinks (Bianchi 2007). The concentration of carbon, nitrogen, and phosphorus in water bodies located at the land-sea interface varies as a function of their input and output, hydrodynamics, water and sediment exchanges, and interactions of biological processes (Buzzelli et al. 2013). Organic matter decomposition and nutrient recycling processes in estuaries and coastal lagoons provide valuable supporting ecosystem services (Lopes and Videira 2013).

However, these ecosystems are often subject to multiple anthropogenic stressors (Fennel et al. 2019) stemming from industrial and agricultural activities on the coastal zone. For instance, effluents from shrimp farms in tropical and subtropical coasts add nutrients, organic matter, and suspended solids to their receiving water bodies (Cardozo, Britto, and Odebrecht 2011; Barraza-Guardado et al. 2013). In some coastal zones, high-frequency climate oscillations are the main driver of biogeochemical and structural variations in the ecosystem (Levin et al. 2015). All these changes affect the nutrient balance and the net ecosystem metabolism (Mackenzie, De Carlo, and Lerman 2011; Staehr et al. 2012). However, the transport, retention, and transformation of materials involved in biogeochemical processes in estuaries and coastal lagoons are strongly influenced by the hydrological and climatic characteristics of each region, as exemplified by the classification of Australian estuaries proposed by Eyre (1998): Mediterranean, temperate, transitional, arid tropical or subtropical, and humid or dry tropical or subtropical estuaries.

At a regional scale, the amount of water and dissolved materials necessary to maintain the optimal metabolism of the system in terms of production and consumption of carbon, nitrogen, and phosphorus, must be estimated and taken into account in the management plans of coastal watersheds (Buzzelli et al. 2013). This can be more easily evaluated and understood by examining nutrient dynamics in undisturbed (pristine) ecosystems (Smith et al. 2012), but also by comparing biogeochemical processes in disturbed and undisturbed coastal water bodies, in terms of their nutrient transfer rates and net metabolism.

The east coast of the Gulf of California comprises several coastal lagoons along a latitudinal gradient encompassing arid subtropical, humid and dry subtropical and tropical climate conditions. This study was carried out in the arid subtropical region, where pristine lagoons as well as lagoons receiving wastewater
from urban areas, agricultural zones, and shrimp farms occur, providing unique opportunities for comparing their biogeochemical functioning. We selected two coastal lagoons, one in pristine conditions and the other receiving effluents from a shrimp farm, to examine their biogeochemical processes using the biogeochemical model developed by the Land-Ocean Interactions in the Coastal Zone (LOICZ) project (Swaney, Smith, and Wulff 2011). The objective of our study was to compare nutrient flux and net metabolism in a pristine lagoon versus a lagoon receiving nutrient inputs through shrimp farm effluents.

Materials and methods

Study area

The study area comprises the El Soldado (ES) and El Rancho (ER) coastal lagoons, both located on the east coast of the Gulf of California (Figure 1). El Soldado lagoon is located 4 km west of Guaymas City (~155,000 inhabitants); it is a federal protected area (BOGES 2006) that does not receive wastewater discharges; therefore, it can be regarded as a pristine system. It has a total area of 1.85 km², 0.60 m average depth, and connects with the Gulf of California through a ~50-m wide, ~2-m deep mouth (Medina-Galván, Audelo-Naranjo, and Arreola-Lizárraga 2019). El Rancho lagoon is adjacent to Empalme city (~60,000 inhabitants); it has a total area of ~8 km², 0.5 m average depth, and connects with the Empalme subsystem through two tidal channels measuring ~20 m wide by ~2 m deep.

The Rancho lagoon receives wastewater from a nearby shrimp farm. The farm has a 44 ha cultivation area and operates from April to October, with an effluent flow rate of 31,290 m³ day⁻¹ during the cultivation cycle (Arreola-Lizárraga et al. 2016). The Empalme subsystem, hereby considered as the sea adjacent to El Rancho lagoon, has a ~16 km² area, 2.3 m average depth, and is connected to the Gulf of California by a 0.4 km-wide mouth (Arreola-Lizárraga et al. 2016).

These coastal lagoons exhibit a mixed semi-diurnal tide (Valle-Levinson, Delgado, and Atkinson 2001) with a 1 m tidal range (Filloux 1973). The climate type in the region is BW (h'), that is, very dry, very warm, or warm (García 2004), with evaporation (2700 mm year⁻¹) exceeding precipitation (230 mm year⁻¹). Rains fall from July to October, with August and May as the rainiest and driest months of the year, respectively; most precipitation is associated with the Mexican monsoon that affects northwest Mexico and southwest United States (Douglas et al. 1993). In the framework of the comparative analysis of Mexican coastal lagoons realized by Arreola-Lizárraga et al. (2018) based on geomorphology expressed as a restriction index (Pr) and water exchange capacity expressed as a saline index, both El Soldado and El Rancho correspond to restricted lagoons with high marine influence.

Biogeochemical model

Nutrient fluxes and net ecosystem metabolism were evaluated using the biogeochemical model developed

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Figure 1. Map of the study area showing the location of El Soldado (ES) and El Rancho (ER) coastal lagoons and sampling sites.
by the Land–Ocean Interaction in the Coastal Zone (LOICZ) project, as described by Gordon et al. (1996).

The model comprises three stages: (1) water budget, (2) salt budget, and (3) budget of non-conservative materials. The general equations used to calculate these budgets are:

\[
dV/dt = V_Q + V_P + V_G + V_O - V_E + V_R \quad (1)
\]

\[
d(V_S)/dt = V_R, S_P - V_E, S_E + V_O, S_O + V_R, S_R + V_X (S_DCN - S_SYS) \quad (2)
\]

\[
d(V_Y)/dt = V_R, Y_R + V_O, Y_O + (Y_{OCN} - Y_SYS) + \Delta Y \quad (3)
\]

Where \( V_Q \) is the stream runoff (assumed to be zero in this case for both lagoons), \( V_P \) is the amount of rainfall, \( V_G \) is the input from groundwater (assumed to be zero in this case for both lagoons), \( V_O \) are shrimp farm effluents (it is zero in El Soldado lagoon, but discharges occur during summer and autumn in El Rancho), \( V_E \) is evaporation, and \( V_R \) remains as the “residual flow” required to balance the water budget. \( S_{DCN} \) and \( S_{SYS} \) are the salinity in the ocean and the system, respectively. \( S_P, S_E, S_O \) and \( S_R \) are the average salinity due to precipitation, evaporation, shrimp farm effluents (it is zero in El Soldado lagoon, but discharges occur during summer and autumn in El Rancho) and residual flow between two boundaries (such as the ocean and the system). \( \Delta Y \) is the flux of non-conservative materials (Dissolved Inorganic Phosphorus, DIP, and Dissolved Inorganic Nitrogen, DIN). \( Y_R \) is the average amount of non-conservative material between two boundaries, \( Y_O \) is the average amount of non-conservative material of shrimp farm effluents (it is zero in El Soldado lagoon, but discharges occur during summer and autumn in El Rancho) and \( Y_{OCN} \) and \( Y_{SYS} \) are the average amount the non-conservative material in the ocean and the system, respectively.

The net ecosystem metabolism (NEM) is given by the difference between carbon production (\( p \)) and respiration (\( r \)), and was estimated with the following equation:

\[
(p - r) = -\Delta\text{DIP}x(C : P)\text{part} \quad (4)
\]

Where \( (C : P)\text{part} \) is the carbon:phosphorus ratio. A system with \( \Delta\text{DIP} > 0 \) is interpreted to be producing DIC via net respiration (\( p - r < 0 \)), while a system with \( \Delta\text{DIP} < 0 \) is interpreted to be consuming DIC via net organic production (\( p - r > 0 \)). For this estimation, the molar ratio C:P = 106:1 was used as determined by Redfield (1934).

The balance between nitrogen fixation and denitrification was estimated with the following equation:

\[
(N_{fix} - \text{Denit}) = \Delta\text{DIN}_{obs} - \Delta\text{DIP}x(N : P)\text{part} \quad (5)
\]

Where \( \Delta\text{DIN}_{obs} \) is the estimated non-conservative flux of DIN and the expression \( \Delta\text{DIP} \times (N : P)\text{part} \) is the expected non-conservative flux of DIN. Assuming that the N:P ratio of particulate material in the system (N:P) part is known, the dissolved nitrogen flux associated with production and decomposition of particulate material is the dissolved phosphorus flux (\( \Delta P = \Delta\text{DIP} + \Delta\text{DOP} \)) multiplied by \((N : P)\text{part}\). It follows, that \((nfix - \text{denit})\) is the difference between the measured dissolved nitrogen flux (\( \Delta N = \Delta NO_3 + \Delta NH_4 + \Delta DON \)) and that expected from production and decomposition of organic matter, assuming the Redfield molar ratio (16:1). The difference between observed and expected \( \Delta DIN \) has been determined to be equivalent to the difference between nitrogen fixation and denitrification.

Water budget, salt budget, nutrients flux, net metabolism, nitrogen fixation, and denitrification were all estimated for each season of the year. The water budget was estimated by integrating data on the water volume in the coastal lagoons and precipitation and evaporation rates over the study period.

Water volumes in El Soldado and El Rancho lagoons were estimated based on their surface area and average depth. The contour and surface of the coastal lagoons were digitized from topographic chart Guaymas G12B11, scale 1: 50,000 (INEGI 1998) using the AutoCad® 2018 graphic editor. Average depth was obtained by bathymetric survey consisting of the spatial distribution of the points recorded in “X” and “Y” coordinates with a receiver unit of the Global Positioning System, using the UTM coordinate system in meters, with Datum WGS 1984. Depth readings were made with a GARMIN GPMAP 188 C graphical echo sounder (Garmin International Inc., Olathe, KS, USA) of dual frequency (50 and 200 kHz), installed on a boat. Sea levels were obtained from tidal predictions for the Guaymas site that corresponds to the location of the El Soldado and El Rancho lagoons, using the software MAR V1.0 developed by CICESE (http://predmar.cicese.mx/programa/) which making tidal predictions in 40 locations in Mexico. Sea level heights were recorded at the beginning and end of the bathymetric surveys to determine elevation changes, compare them with predictions, and correct depth readings. Water volumes were computed using the software CivilCAD® (CivilCAD 2012).

Precipitation and evaporation data for the study period were obtained from a weather station located 3 km east from El Rancho lagoon (Figure 1) and operated by the Comisión Nacional del Agua (National Water Commission). The daily evaporation and precipitation data were used to estimate seasonal water budgets of each coastal lagoon.

**Water quality sampling**

A regular grid of sampling sites encompassing the water body and the adjacent sea was set on each coastal lagoon (Figure 1). Water quality sampling was
conducted on three occasions with a weekly frequency in a representative month of each season of the year: winter (February), spring (March), summer (June) and autumn (November) at 8 sampling sites in El Soldado (n = 24 for each season) and 3 sampling sites in adjoining sea (n = 9 for each season), as well as at 5 sampling sites in El Rancho (n = 15 for each season) and 8 sampling sites in adjoining sea (24 for each season). Temperature, salinity, and dissolved oxygen were recorded in situ at each sampling site using an autonomous Hydrolab Multi parameter Data Sonde. A subsurface water sample was also collected at each sampling site using an airtight 1 L plastic container, and tested for the concentration of nitrates, nitrites, ammonium, and orthophosphates. The water samples were filtered through 1 μm, type A/E Gelman filters. Dissolved inorganic nutrients were determined with the methods described by Strickland and Parsons (1972).

**Data analyses**

Values of temperature, dissolved oxygen, salinity, and nutrient concentrations in water (DIN = nitrite, nitrate, and ammonium; DIP = orthophosphate) for each season were analyzed between the lagoons by comparison of means with one-way analysis of variance. A significance level of p < 0.05 was used for all tests. The results are shown by means of box-and-whisker graphs. All tests and graphs were performed with the statistical package STATGRAPHICS Plus 4.1.

**Results**

**Water quality**

Water temperature attained the highest value (30°C) in summer and the lowest (~18°C) in winter in both lagoons. There were significant differences in temperature between the lagoons in spring (El Soldado lagoon > El Rancho lagoon) and autumn (El Rancho lagoon > El Soldado lagoon). The difference was ~ 3°C in both cases (Figure 2a).

Water salinity varied between 35 and 39 psu over the year in both lagoons. Salinity values in El Rancho were higher than in El Soldado in all seasons. There were significant differences in salinity between the two lagoons in summer, when average salinity was ~36 psu in El Soldado and ~38 psu in El Rancho (Figure 2b).

The concentration of dissolved oxygen in water varied between 4 and 7.5 mg L\(^{-1}\) over the year in both lagoons. The lowest concentrations (4 mg L\(^{-1}\) on average) of dissolved oxygen were recorded in summer in both lagoons. Dissolved oxygen concentration in El Soldado was consistently higher than in El Rancho in all seasons (Figure 2c).

The concentration of dissolved inorganic nitrogen (DIN) showed little variation (0.05–1.5 μM) for most of

![Figure 2](image_url). Comparison of the seasonal variability of a) temperature, b) salinity, c) dissolved oxygen, d) DIN dissolved inorganic nitrogen -nitrite,nitrate,ammonium- and e) DIP dissolved inorganic phosphorus -orthophosphate- in the El Soldado (ES) and El Rancho (ER) coastal lagoons. Median, quartiles, ranges, and outliers of data are shown for each variable in each season comparing between lagoons.
the year, except in winter, when DIN reached an average value of 4.5 μM in El Soldado and 12.1 μM in El Rancho (Figure 2d).

The lowest concentrations of dissolved inorganic phosphorus (DIP) were recorded in summer (0.8 and 1 μM) and autumn (0.5 and 0.9 μM) in El Soldado and El Rancho lagoons, respectively. The highest DIP concentrations were recorded in the winter in both lagoons, with average values of 1.50 μM in El Soldado and 2.22 μM in El Rancho (Figure 2e).

Biogeochemical budget

Water and salt budgets
Water budgets for each season showed that flushing time in El Soldado lagoon was highest in spring (3.2 days) and lowest in winter (1.1 days), while El Rancho lagoon showed flushing time highest in summer (1.6 days) and lowest in spring (0.4 days) and autumn (0.5 days) (Figure 3).

Nutrient fluxes
Nutrient budgets for each season showed the nutrients inputs seasonal due to both anthropogenic and natural influences. DIN and DIP fluxes were higher in El Rancho than El Soldado. In both lagoons DIN and DIP fluxes were higher in winter than during the others seasons (Figure 4).

The analysis of nutrient fluxes showed that El Soldado acted as a source of DIN during the spring, exporting it to the adjacent sea, but acted as a sink during the summer, autumn, and winter when it became a net importer of DIN. The highest DIN transfer rates were recorded in winter. The El Rancho lagoon exported DIN in spring and summer and imported it in autumn and winter; the highest export and import rates were recorded in summer and winter, respectively (Figure 5a).
Both systems acted as sources of DIP in summer, but the rate of transfer from El Rancho lagoon to the adjacent sea was higher. Both lagoons acted as sinks in spring, autumn, and winter; the highest import rate was recorded in El Rancho lagoon in autumn (Figure 5b).

**Net ecosystem metabolism**

The two lagoons exhibited an autotrophic net metabolism in the spring, autumn, and winter. The highest autotrophy rates were recorded in El Rancho lagoon in autumn. Both lagoons showed a heterotrophic net metabolism in summer, but...
the El Rancho lagoon had a higher metabolic rate (Figure 5c).

Nitrogen fixation exceeded denitrification in spring, autumn, and winter in both lagoons; the highest fixation rate was recorded in El Rancho in autumn. Denitrification was recorded in both lagoons in summer, with a higher rate in El Rancho (Figure 5d).

Discussion

Nutrient dynamics and net metabolism showed differences between the pristine lagoon (El Soldado, ES) and the one receiving effluents from a shrimp farm (El Rancho, ER). These differences seem to be associated with the input of nutrients and organic matter through the shrimp farm effluent, since such inputs are known to cause increases in the concentration of nutrients, organic matter, and suspended solids in the receiving water bodies (McKinnon et al. 2002; Cardozo, Britto, and Odebrecht 2011). The effects of such inputs on biogeochemical processes depend on (1) the volume and composition of the discharges, (2) the water quality prevailing in the receiving water bodies, and (3) the dilution rate, assimilation capacity, flushing time, and tidal regime (Páez-Osuna 2001; Barraza-Guardado et al. 2015).

ES and ER are both arid subtropical lagoons that are euhaline (35–39 psu), with little variations in salinity during the year. Both show marked seasonal variations in water temperature with a maximum (~32°C) in summer and a minimum (~16°C) in winter; and moderate seasonal variations in dissolved oxygen (summer: ~4 mg L⁻¹, winter: ~8 mg L⁻¹). The similar seasonal variations in water temperature are due to their both being shallow water bodies (<2 m average depth), which allows the rapid heating or cooling of the water column driven by seasonal changes in solar radiation and heat exchange with the atmosphere (Uncles and Stephens 2001). Thus, air temperature above these lagoons, located in an arid region, exhibits annual ranges wider than 14°C (Garcia 2004). This, together with the daily advection of water masses from the adjacent sea – whose surface temperature typically ranges from 26°C in summer to 17°C in winter (Rodén and Emilsson 1980) – to the lagoons, explain the seasonal variations in water temperature.

The high but narrowly varying water salinity values (35–39 psu) observed in both systems can be accounted for by the high evaporation (~3000 mm year⁻¹) and low precipitation (<300 mm year⁻¹) in this semi-arid subtropical region (Arreola-Lizárraga et al. 2016), since rains and the ensuing runoff are the only input of freshwater into these lagoons. In addition, tides cause a daily exchange of water between the lagoons and the adjacent sea. The higher salinity values recorded in ER, compared to those in ES, can be attributed to the input of shrimp-farm effluents with salinity levels over 40 psu due to water evaporation in culture ponds (Barraza-Guardado et al. 2013).

Dissolved oxygen (DO) values showed an inverse behavior to that of water temperature. This is partly accounted for by the fact that oxygen solubility decreases as temperature and salinity increase (Best, Wither, and Coates 2007). However, the decrease in DO
concentration in summer was also caused by the faster decomposition of organic matter due to increased bacterial activity as water temperature rose. Average DO concentrations were above 4 mg L\(^{-1}\), which can be mainly attributed to the photosynthetic activity of phytoplankton and macroalgae (Arreola-Lizárraga et al. 2016; Ruiz-Ruiz et al. 2016; Mata-Ángeles et al. 2019), the fast flushing time that characterizes lagoons in this subtropical region (Arreola-Lizárraga et al. 2016; Ruiz-Ruiz et al. 2016, 2017), and the gaseous exchange with the atmosphere driven by the seasonal wind pattern in this part of the Gulf of California, with more intense winds in winter than in summer (Paredes-Sierra et al. 2003).

The highest concentrations of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) were recorded in winter in both lagoons. This is attributed to the coastal upwelling events that commonly occur from October to March in this part of the Gulf of California (Lluch-Cota 2000). Coastal upwellings are known to promote nutrient enrichment in coastal lagoons due to their daily exchange of water with the sea, as observed in this part of the east coast of the Gulf of California (Arreola-Lizárraga et al. 2016; Ruiz-Ruiz et al. 2017) and other regions of the Pacific Ocean such as the Magdalena (Cervantes-Duarte 2016) and San Quintín (Camacho-Ibar, Carriquiry, and Smith 2003; Ribas-Ribas et al. 2011) lagoons. It has also been observed that primary production in estuaries of the Pacific Northwest coast (USA) – which are subject to heavy tidal influence and very high seasonal fluvial inputs – is controlled by coastal upwelling and exchange with the ocean rather than by the stratification induced by rivers (Hickey and Banks 2003).

Nutrient concentrations were lower in spring, summer, and autumn in both lagoons. The major sources of nutrients in those seasons are (1) internal recycling, (2) runoff associated with rains in this semi-arid region (<300 mm year\(^{-1}\)) (Arreola-Lizárraga et al. 2016), and (3) nutrient inputs from the shrimp farm to the ER system.

Flushing times were shorter than four days in both lagoons. This is explained by the intense evaporation (~3000 mm year\(^{-1}\)), which affects the volume of water leaving the system and must be compensated by the entry of water from the adjacent sea. Low flushing time rates favor nutrient assimilation and dilution, but also limit the growth of phytoplankton biomass and accumulation of organic matter; all this reduces the eutrophication susceptibility of the lagoons (Scavia and Liu 2006; Whitall et al. 2007; Garmendia et al. 2012). Flushing times shorter than 10 days were also observed in the Guaymas (Ruiz-Ruiz et al. 2016) and Lobos (Ruiz-Ruiz et al. 2017) lagoons, as well as El Sargento, La Cruz, Las Guasimas lagoons, also located in this semi-arid subtropical region showed flushing times <21 days (Table 1), and other water bodies located on others subtropical regions has exhibited flushing times ~20 days as San Quintín, Caloosahatchee River,

Table 1. Flushing time, nutrient fluxes, net metabolism and fixation-denitrification estimated by LOICZ biogeochemical model in several Subtropical coastal lagoons of America.

| Systems          | Period  | Area (km\(^2\)) | Flushing time (day) | ΔDIN (mmol m\(^{-2}\) day\(^{-1}\)) | ΔDIP (mmol m\(^{-2}\) day\(^{-1}\)) | P-R (mmol C m\(^{-2}\) day\(^{-1}\)) | nfix-denit (mmol m\(^{-2}\) day\(^{-1}\)) |
|------------------|---------|-----------------|---------------------|------------------------------------|------------------------------------|-------------------------------------|--------------------------------------|
| 1 El Soldado      | spring  | 1.8             | 3.2                 | 0.033                              | -0.023                             | 2.46                                | 0.4                                  |
|                  | summer  | 1.2             | -0.021              | 0.035                              | 3.7                                | -0.45                               |
|                  | fall    | 2.4             | -0.011              | -0.033                             | 3.54                               | 0.52                                |
|                  | winter  | 1.1             | -0.413              | -0.093                             | 9.87                               | 1.08                                |
|                  | annual  | 2               | -0.103              | -0.028                             | 3.04                               | 0.387                               |
|                  | spring  | 7.8             | 0.4                 | 0.018                              | -0.080                             | 8.53                                | 1.3                                  |
|                  | summer  | 1.6             | 0.125               | 0.153                              | -15.44                             | -2.21                               |
|                  | fall    | 0.5             | -0.042              | -0.251                             | 26.6                               | 3.97                                |
|                  | winter  | 0.9             | -0.970              | -0.092                             | 9.73                               | 0.5                                  |
|                  | annual  | 0.8             | -0.217              | -0.067                             | 7.35                               | 0.89                                |
| 2 El Sargento     | summer  | 11              | 5                   | -0.110                             | 0.380                              | -41                                 | -6                                   |
|                  | winter  | 14              | -0.020              | -0.080                             | 8                                  | 1.3                                  |
| 3 La Cruz         | summer  | 23              | 21                  | 0.036                              | 0.0240                             | -2                                  | -0.4                                 |
| 4 Guasimas        | summer  | 37              | 3                   | 0.170                              | 0.020                              | -1.7                                | -0.1                                 |
| 5 Lobos           | summer  | 101.6           | 5                   | 0.004                              | -0.060                             | -0.38                               | -0.1                                 |
|                  | winter  | 12              | -1.340              | -0.150                             | 16.49                              | 1.1                                  |
| 6 Magdalena       | upwelling intense | 565  | 338                                              | -0.230                             | -0.008                             | 0.90                               | -0.10                                |
|                  | Upwelling weak |             |                     | -0.110                             | 0.020                              | -2.11                               | -0.42                                |
|                  | winter  | 42              | 14                  | -0.290                             | 0.710                              | -31                                 | -3.9                                 |
|                  | annual  | 56              | 18.4                | 3.917                              | 0.437                              | -45.3                               | -3.1                                 |
| 7 San Quintin     | winter  | 22              | 11.3                | 0.173                              | -1.006                             | 97.6                                | 16.3                                 |
|                  | annual  | 330             | 12                  | -0.022                             | 0.019                              | -4.1                                | -3                                   |
| 8 Caloosahatchee River | winter  | 4.2             | 11.3                | 0.015                              | 0.325                              | -1.3                                | 0.4                                  |
| 9 St. Lucie River | annual  |                |                     |                                    |                                    |                                     |
| 10 Madre’s Estuary System | annual |                |                     |                                    |                                    |                                     |

References: 1 This Study; 2 Almeda (1999); 3 Botello-Ruvalcaba and Valdez-Holguín (1997); 4 Padilla-Arredondo, Arreola-Lizárraga, and Lechuga-Devéze (2000); 5 Valenzuela-Siu et al. (2007); 6 Cervantes-Duarte (2016); 7 Camacho-Ibar, Carriquiry, and Smith (2003); 8 Buzzelli et al. (2013); 9 Marone et al. (2000) 10 Cabral and Fonseca (2019).
St. Lucie River, Paranagua bay, and Madre’s Estuarine System (Table 1), which made all these systems less susceptible to eutrophication.

**Nutrient fluxes**

The analysis of nutrient fluxes showed that ER had higher rates than ES, with both systems acting as nutrient sinks for most of the year. Specifically, nutrient transfer rates from shrimp farm effluents to El Rancho represented ~45% of the DIN and ~15–20% of the DIP during summer and autumn. This propagated an increase in both DIN and DIP fluxes by four or more orders of magnitude compared to those observed at El Soldado for those seasons.

Nitrogen fluxes increased in winter in both systems in response to the input of nutrients from the adjacent sea associated with upwelling events at this time of the year (Lluch-Cota 2000). When coastal upwellings occur, the nutrients transfer rates from sea to lagoons are highest of the year. It was estimated that El Rancho received ~77% of DIN and ~33% of DIP, while El Soldado ~40% of DIN and ~26% of DIP. Our results showed that these water bodies responded to the input of DIN by increasing flow rates and acting as sinks.

Coastal upwellings also explain the faster rate observed in ES as a phosphorus sink in winter. However, the fastest flux of DIP in ER was recorded in autumn. This is the time of the year when shrimp are harvested and all the water contained in culture ponds is discharged – carrying phosphorus-rich sediments – into ER. It has been documented that only ~20% of the phosphorus contained in feed is converted into shrimp biomass and the rest is released to the environment (Barraza-Guardado et al. 2015).

In the nutrient budget, our results showed that both ER and ES had higher transfer rates in autumn and winter and acted as sinks. The responses of estuaries and coastal lagoons to nutrient inputs, acting as either sources or sinks, are diverse (e.g., Padedda et al. 2010; Noriega and Araujo 2011; Buzzelli et al. 2013) as is also observed in other subtropical lagoons of America (Table 1). Our results coincide with observations for the Lobos lagoon in this same region of the Gulf of California. This lagoon responded to the input of nutrients from wastewater and coastal upwellings with an increased nutrient flux, acting as a sink during winter (Valenzuela-Siu et al. 2007). This suggests that the subtropical lagoons on the east coast of the Gulf of California respond with increased nutrient flow rates, acting as sinks, at least during nutrient-input periods driven by coastal upwellings.

Our findings from the nutrient budget suggest that the ES and ER lagoons acting predominantly as nutrient sinks are consistent with what Nixon et al. (1996) observed in North Atlantic estuaries, where estuarine processes retain and remove 30–65% of total N and 10–55% of total P.

The evidence presented shows the utility of the LOICZ model as a simple and practical tool to understand the nutrient dynamic and responses from coastal lagoons that receive nutrients from anthropogenic sources (in this case, shrimp farms effluents) and natural sources (in this case, seasonal coastal upwelling).

**Net ecosystem metabolism**

The ER and ES lagoons showed a dominance of autotrophic metabolism in spring, autumn, and winter, and a dominance of heterotrophic metabolism in summer. This seasonal pattern of net metabolism is consistent with the findings of Valenzuela-Siu et al. (2007) for the Lobos lagoon, in this same region of the Gulf of California, which exhibited dominant processes of autotrophic metabolism in winter and heterotrophic in summer.

ES showed higher differences between production and respiration in winter (9.9 mmol C m⁻² day⁻¹), but lower than 4 mmol C m⁻² day⁻¹ in the rest of the year. Estimates between production and respiration in ER were consistently higher, particularly in summer (~15.4 mmol C m⁻² day⁻¹) and autumn (26.6 mmol C m⁻² day⁻¹). This difference in p-r shows that ER responds to the input of nutrients from shrimp farm effluents in summer and autumn by increasing its net metabolism. However, ER does not receive shrimp farm effluents in winter and it then responds to the input of nutrients from upwelling with differences between production and respiration similar to those observed in the pristine ES system; production predominates over respiration processes in both systems. This demonstrates that ER can assimilate the extra nutrients received in summer and autumn by increasing its net metabolic rate, and also shows the magnitude of the ensuing change in metabolism when compared to the pristine ES system.

The dominance of heterotrophic net metabolism observed in summer in both systems is explained by the warm water conditions (temperature ~ 30°C) that prevail at this time of the year, which favor an increased bacterial activity and organic matter oxidation (Caffrey 2004). At this time of the year both lagoons receive a higher input of organic matter from runoff and in mangrove litter (Arreola-Lizárraga, Flores-Verdugo, and Ortega-Rubio 2004), which favors an increase in ecosystem respiration rates. The ER lagoon receives additional organic matter inputs through shrimp farm effluents, which explains its higher differences between production and respiration relative to the ES lagoon.

**Nitrogen fixation/denitrification**

Nitrogen fixation processes predominated in spring, autumn, and winter in both lagoons. The N₂ fixation dominated in ES and it was twice as high in winter
(1 mmol m⁻² day⁻¹) than in spring and autumn (~0.5 mmol m⁻² day⁻¹) in response to the input of DIN from coastal upwelling, using up the DIN and increasing the dominance of autotrophic metabolism. However, the N₂ fixation dominated in ER and it was lower in winter (0.5 mmol m⁻² day⁻¹) than in spring (1.3 mmol m⁻² day⁻¹) and autumn (~4 mmol m⁻² day⁻¹). The dominance of N₂ fixation estimated in spring suggests that this is an important source of nitrogen that favors autotrophic metabolism, as observed in other subtropical systems (Eyre and McKee 2002).

The high N₂ fixation in autumn is a source of nutrients in addition to those in shrimp effluents, which are then consumed in the system to support production and enable the autotrophic metabolism observed.

In both systems, denitrification was the prevalent process in summer. This is explained by the environmental conditions prevailing in the system at this time of the year, with high water temperature (~30°C) coupled with the lowest dissolved oxygen concentration (~4 mg L⁻¹). Pielicher and Smyth (2011) also observed seasonal denitrification patterns in various estuarine habitats, with higher rates during the warm season, as well as a strong correlation between denitrification and oxygen demand in the sediments. The dominance of denitrification estimated in the ER (~2.21 mmol m⁻² day⁻¹) were more than four-fold higher than those estimated in the ES (~0.45 mmol m⁻² day⁻¹). This can be explained by the additional input of nitrogen in shrimp farm effluents entering the ER, which caused an increase in the denitrification process in summer. This evidence the ecosystem service provided by this system – removal of excess nitrogen –, in addition to nutrient recycling.

Coastal lagoons such as El Rancho and others sub-tropical systems of America with area <100 km² (Table 1) which are subjected to high material loading and fast flushing are very important components in biogeochemical cycling at the local, regional, and global scales (Smith et al. 2005), as reported Buzzelli et al. (2013) for Caloosahatchee and St. Lucie estuaries. In addition, pristine systems such as El Soldado are useful references in detecting biogeochemical processes changes such as observed in this study.

**Conclusion**

Our results contribute to better understand the biogeochemical functioning of subtropical lagoons. Our results are also consistent with those obtained by Valenzuela-Siú et al. (2007) that semi-arid subtropical coastal lagoons of the Lower Gulf of California oceanographic province experience marked seasonal changes: denitrification processes are dominant and net metabolism is heterotrophic in summer, while nitrogen fixation processes become dominant and net metabolism is autotrophic in winter.

The detailed comparison between a pristine system (ES) and a system receiving shrimp farm effluents (ER) revealed the magnitude of the changes occurring in the rates and behavior of nutrient flows, net metabolism, N₂ fixation, and denitrification processes. This information is useful for improving the environmental management of coastal lagoons. For the Gulf of California, it is important to undertake further studies and expand data series of coastal lagoons considering the influence of climate change.

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