

The effectiveness of restoration actions on the biogeochemistry of a polluted Caribbean coastal lagoon

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Summary: Coastal lagoons are exposed to a variety of stressors, including natural and anthropogenic ones. Due to the rapid degradation of many of these lagoons, environmental and governmental authorities have implemented actions to restore their original or stable state, and hence the ecological functions of these ecosystems. Laguna Larga is a highly impacted and polluted Caribbean coastal lagoon in Cuba. It has low water transparency, high nutrient and eutrophication levels and a low dissolved oxygen concentration. Between 2010 and 2012, restoration actions such as dredging and channel opening were implemented to improve water quality and trophic conditions. Some physicochemical parameters and nutrients were determined between 2010 and 2014 at 12 sites inside the lagoon. To detect significant differences among the parameters assessed, a non-parametric Kruskal-Wallis test was used. Since the samples were not taken at regular time intervals and to handle missing data in our dataset by applying the non-parametric Mann-Kendall test, the missForest machine learning method was used. The concentration of nutrients, oxygen and salinity was similar to that of previous studies and showed an increase in nutrients and in the trophic state from the outer to the inner section of the lagoon. Salinity (0.2 per year) and dissolved oxygen (0.1 mg/L) showed a slight but significant decreasing trend. All the nutrients measured (except dissolved inorganic nitrogen) showed a significant decreasing trend after the restoration actions. Laguna Larga is an impacted tropical lagoon that needs more actions to restore the ecosystem, including the closure of wastewater discharge points and seawater pumping from the adjacent ocean.

Keywords: recovery; trend; lagoon; nutrients; trophic status; Caribbean.

La efectividad de acciones de restauración sobre la biogeoquímica de una laguna costera contaminada del Caribe

Resumen: Las lagunas costeras están expuestas a una variedad de factores estresantes, que incluyen factores naturales y antropogénicos. Debido a la rápida degradación de muchas de estas lagunas, las autoridades ambientales y gubernamentales han implementado acciones para restaurar su estado original o la estabilidad de las mismas y, por ende, las funciones ecológicas de estos ecosistemas. Laguna Larga es una laguna costera caribeña altamente impactada y contaminada en Cuba. Tiene baja transparencia del agua, altos niveles de nutrientes y eutrofización, así como baja concentración de oxígeno disuelto. Entre 2010 y 2012 se implementaron acciones de restauración, tales como dragado y apertura de canales, para mejorar la calidad del agua y las condiciones tróficas. Se determinaron algunos parámetros fisicoquímicos y de nutrientes entre 2010 y 2014 en 12 sitios dentro de la laguna. Para detectar diferencias significativas entre los parámetros evaluados se utilizó la prueba no paramétrica de Kruskal-Wallis. Dado que las muestras no se tomaron a intervalos de tiempo regulares, y para manejar los valores que faltan en nuestro conjunto de datos coleccionado usando el método no paramétrico de Mann-Kendall, se utilizó el método de aprendizaje automático missForest. Las concentraciones de nutrientes, oxígeno y salinidad fueron similares a las de estudios anteriores, y mostraron un aumento de los nutrientes y del estado trófico desde la sección exterior hacia la interior de la laguna. La salinidad (0,2 por año) y el oxígeno disuelto (0,1 mg/L) mostraron una tendencia decreciente leve pero significativa. Todos los nutrientes medidos (excepto DIN) mostraron una tendencia decreciente significativa después de las acciones de restauración. Laguna Larga es una laguna tropical impactada que necesita más acciones, incluido el cierre de puntos de descarga de aguas residuales y el bombeo de agua de mar desde el océano adyacente, para lograr la restauración del ecosistema.

Palabras clave: recuperación; tendencia; laguna; nutrientes; estado trófico; Caribe.

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INTRODUCTION

Because of the importance of marine coastal ecosystems, scientists have assessed the risks and pressures to which coastal lagoons are exposed (Pérez Ruzafa et al. 2019, Newton et al. 2020). One of the pressures is the impact related to human activities such as industrialization (Borja et al. 2006, Díez et al. 2009), agriculture and mining (Greening and Janicki 2006), dredging (Sheridan 2004), sewage disposal (Adu-Boahen 2018) and tourism (González-De Zayas et al. 2018).

Human and natural impacts alter some of the biogeochemical processes of lagoon water and sediments (Newton et al. 2020). The most common biogeochemical alteration is the anthropogenic eutrophication process, which degrades water quality and other biological functions due to the accumulation of nutrients and organic matter from human activity, resulting in the rapid development of algae and aquatic plants (Padedda et al. 2019).

For this reason, environmental and governmental authorities design and implement management actions to protect coastal lagoon ecosystems. Most of these actions are restoration projects (Boscolo Brusà et al. 2022) and may include eco-engineering measures to restore and modify flow regimes and water exchange, bottom elevation alterations, and elimination or reduction of nutrient loads (Borja et al. 2010, Boscolo Brusà et al. 2022, Newton et al. 2020).

Because of the great variability of these environments the effectiveness of restoration actions in coastal lagoons depends on many factors, such as the exchange with the adjacent sea, tidal conditions, climate conditions, bathymetry, morphology, and economic activities associated with lagoons (fishing, mining and agriculture)(Gikas et al. 2006, Padedda et al. 2019). Most authors agree that making recovery predictions is very difficult, and that the best way to evaluate the effects of these actions is the continuous monitoring of the lagoon's ecological conditions, including water quality (Gikas et al. 2006, Padedda et al. 2019, Boscolo Brusà et al. 2022).

Laguna Larga has been thoroughly investigated (González-De Zayas et al. 2021) in studies on water quality and nutrient fluxes (González-De Zayas et al. 2013, 2018), heavy metals in sediments (González-De Zayas et al. 2020), primary productivity of macroalgae and phytoplankton (Guimaraes Bermejo and González-De Zayas 2011), molluscs (Olivera Espinosa 2013) and fish assemblages (Salvat Torres et al. 2013).

Over the last three decades, this lagoon has been subjected to numerous stressors, including road building, dredging, filling of parts of the lagoon to build hotels, disposal of sewage, and excessive growth of mangroves that isolate the inner sections of the lagoon and limit water exchange with the adjacent sea (González-De Zayas, et al. 2013, 2018, 2021).

González-De Zayas et al. (2013) found a long water residence time (between 0.1 and 0.7 years), some hypoxia ($<3 \text{ mg L}^{-1}$) and anoxia events ($<1 \text{ mg L}^{-1}$) and high contents of total nitrogen (up to $475 \text{ } \mu\text{M}$) and phosphorus (up to $14.5 \text{ } \mu\text{M}$) in the inner section of the lagoon. They concluded that Laguna Larga was a eutrophic system. The same trophic behaviour for Laguna Larga was described by González-De Zayas et al. (2018): a spatial pattern of increasing eutrophication from the sea and the outer sector (oligotrophic-mesotrophic) to the central (mesotrophic) and the inner sector (mesotrophic-eutrophic). Both studies report that restrictions to hydrodynamics inside the lagoon and sewage from hotels have largely contributed to the lagoon's pollution.

From April 2010 to March 2012, some actions were implemented to increase water exchange of the inner and central sections of the lagoon with the outer section and with the adjacent sea. These actions included dredging of the exchange channel that connects the inner and outer lagoon sections, sediment removal from the Tryp Hotel area, removal of mangrove trees from the main channel, and removal of obstacles (construction waste, old pipelines and garbage) tipped under the bridge over the central section and in the rest of the lagoon area (Fig. 1).

Monitoring of water quality, considering some physical and chemical parameters as indicators to find trends before and after management actions on aquatic ecosystems, is one of the tools that can be used to know whether such actions are effective (Newton et al. 2020).

The hypothesis of this study was that if these restoration actions were effective, the water quality of Laguna Larga (as a whole ecosystem) would have improved. To this end, our principal objective was to evaluate the impact of the actions undertaken between 2010 and 2012 on the biogeochemistry of the lagoon indicators.



Fig. 1. – Some restoration implemented actions at Laguna Larga between 2010 and 2012. A, filling of road to dredge the channel; B, dredged channel; C, dredging of channel at the central section; and D, cutting of red mangrove roots.

MATERIAL AND METHODS

Study area

Laguna Larga is a typical coastal lagoon located on the northern coast of Cayo Coco, Cuba (Sabana-Camagüey Archipelago) (Fig. 2). According to González-De Zayas et al. (2013), Laguna Larga is classified as a choked lagoon based on the criteria of Kjerfve and Magill (1989). It has limited water exchange with the adjacent sea, with a long water residence time of up to 251 days (González-De Zayas et al., 2018). The area of the lagoon is approximately 0.32 km², with a mean depth of 0.9 m (with reference to mean sea level). The lagoon exchanges water with the adjacent sea through a narrow channel (15 m wide during high tide and 7 m wide during low tide). González-De Zayas et al. (2018) suggested that considering morphology, hydrodynamics and biogeochemistry, this lagoon could be divided into three sections: the outer section (eastern part), and the central and inner sections (western part). The outer and central sections are covered by a dense red mangrove forest, so the inner section is practically isolated.

The lagoon area has a tropical climate with a mean annual rainfall of about 1129 mm, 70% of which occurs from May to October (the wet period) and the rest from November to April (the dry period). The trade winds from the E-NE prevail in the region. The mean annual air temperature is 26°C, with a minimum value of 22.8°C in the dry period and a maximum of 27.8°C in the wet period (ACC/ICGC 1990).

Field sampling

Sampling was carried out between 2010 and 2014 (Table 1) over a site network evenly distributed across the lagoon (12 sites), and one site in the adjacent sea to the north of the lagoon (Fig. 2).

Table 1. – Laguna Larga sampling dates between 2010 and 2014.

	Sampling date	Sites	Period	Item
2010	April	12	Before	S1
	September	12	During	S2
	January	12	During	S3
2011	June	12	During	S4
	September	12	During	S5
	December	12	During	S6
	March	12	During	S7
	May	12	After	S8
2012	September	12	After	S9
	November	12	After	S10
	December	12	After	S11
	February	12	After	S12
	May	12	After	S13
2013	July	12	After	S14
	September	12	After	S15
	December	12	After	S16
	February	12	After	S17
2014	May	12	After	S18
	August	12	After	S19
	December	12	After	S20

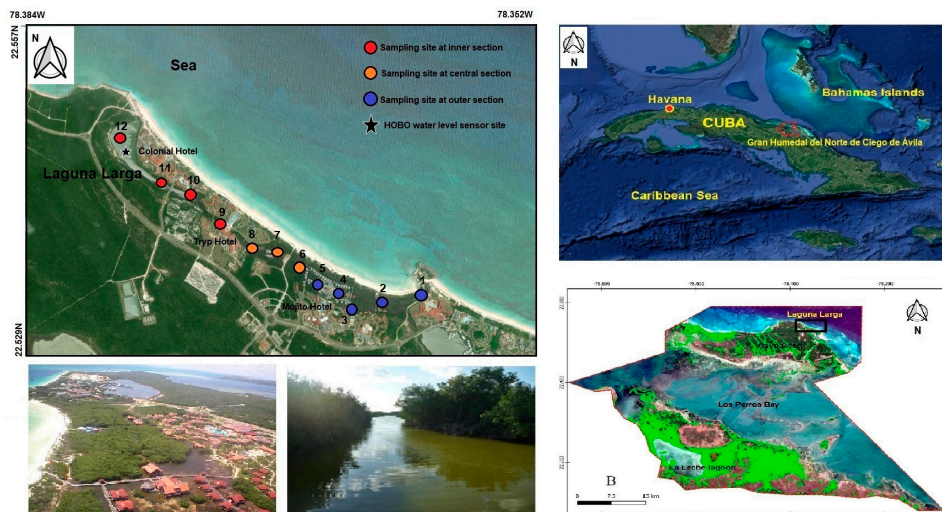


Fig. 2. – Location and sampling sites in Laguna Larga, Cuba.

Water temperature and salinity were determined in situ, using a WLW digital thermo-salinometer (precision of equipment is 0.1°C of temperature and 0.1 of salinity). Dissolved oxygen (DO) was determined in triplicate using the Winkler method (Wright 1983). Nutrient (dissolved inorganic nitrogen: $\text{DIN} = \text{NH}_4^+ + \text{NO}_2^- + \text{NO}_3^-$) and soluble reactive phosphorus (SRP) were immediately filtered through Millipore filters of $0.22\ \mu\text{m}$ and fixed with chloroform. Filtered and unfiltered samples were frozen until total nitrogen (TN) and phosphorus (TP) analyses were performed. Dissolved nutrients were analysed separately with a Skalar San Plus segmented-flow autoanalyser, using the standard methods adapted by Grasshoff et al. (1983) and the circuits suggested by Kirkwood (1994). Unfiltered samples for TN and TP analysis were held in polypropylene containers and analysed as nitrate and SRP after being oxidized at high temperature (120°C) with persulfate in an autoclave for 30 minutes, following Valderama (1981). Organic nitrogen and organic phosphorus were calculated by subtraction (see González-De Zayas et al. 2013 for details).

Karydis trophic index

One of the trophic indexes used for coastal water is the one proposed by Karydis et al. (1983). This index, known as the Karydis trophic index (KTI), was calculated in this study for DIN and SRP at 12 sampling sites inside Laguna Larga, using the following equation:

$$KTI = \frac{C}{C - \log X} - \log A$$

where C is the sum of nutrients (DIN and SRP) at each sampling site, X is nutrient concentration (DIN and SRP) at each sampling site, and A is the number of sampling sites (12). KTI (dimensionless) generates a continuous evaluation of eutrophication where the scale is oligotrophic ($\text{KTI} < 3$), mesotrophic ($3 \leq \text{KTI} \leq 5$), and eutrophic ($\text{KTI} > 5$).

Water level variation

An Onset HOB0 data logger (0.21 cm of water level resolution and 0.001°C of water temperature) was placed inside the inner section of Laguna Larga from 2011 to 2014 (Fig. 2). The data logger recorded pressure and temperature every two minutes. Data were processed monthly using HOBOWare Pro (version 3.7.13). Logger data were collected from February 2012 to June 2012. The channel that connects the central and outer sections of the lagoon was reopened in March 2012.

Statistical analysis

A descriptive statistic of each physicochemical and nutrient concentration determined was calculated using the XLSTAT program (version 2016.02.28451). Using the same software, the differences of these parameters among sections of the lagoon (non-parametric Kruskal-Wallis test, for significance level of 0.05) were assessed.

Since the samples were not taken at regular time intervals, and to handle missing data in our dataset by applying the non-parametric Mann-Kendall test, we used the missForest machine learning method. The package used in R (version 1.5) was missForest (Stekhoven and Bühlmann, 2012; Stekhoven, 2022).

missForest is an iterative imputation method based on Breiman's Random Forest algorithm (Breiman, 2001). This algorithm can estimate imputation errors without the need for a test suite by using out-of bag (OOB) error estimates. OOB error, also known as OOB estimation, is a way to estimate the prediction error of random forests, boosted decision trees and other machine learning models using bootstrap aggregation (bagging). Bagging creates training samples for model learning by using subsampling with replacement. In other comparative studies, missForest outperformed other imputation methods, especially in data environments where complex interactions and nonlinear relationships are suspected. missForest's OOB error estimates are adequate in all environments (Waljee et al., 2013; Shah et al., 2014) and an accurate and reliable indicator of imputation performance. To verify the performance of imputation of missing data, we used not only OOB error estimation but also a non-parametric Kruskal-Wallis test between real and imputed data.

The Mann-Kendall test (Sneyers 1992) was used to detect trends during the analysed time period (2010–2014). This test was applied using the XLSTAT program (version 2016.02.28451).

RESULTS

Water quality of the entire lagoon and its sections

The descriptive statistics (physicochemical and nutrients) for the whole lagoon and each section (inner, central and outer sections) are shown in Table 2. Mean water temperature was directly related to the season: the highest values (around 30.0°C) were recorded during August and September. Mean salinity was significantly different among the three sections ($p < 0.05$), with the lowest salinity (30.5) in the inner section and the highest (35.9) in the outer section, similar to the mean salinity of the adjacent sea). In contrast, dissolved oxygen levels remained relatively stable, with mean values around 3.0 mg L⁻¹ across all lagoon sections. Anoxia (less than 1 mg L⁻¹) and hypoxia (less than 3 mg L⁻¹) were recorded only at one site of Laguna Larga during the sampling period (site 9).

Table 2. – Mean concentrations ± standard deviation of the physicochemical parameters and nutrients determined in the whole lagoon (Laguna Larga) and its sections for the whole sampling period (2010–2014). Superscript letters denote significant differences. DO, dissolved oxygen; DIN, dissolved inorganic nitrogen; SRP, soluble reactive phosphorus; SRSi, soluble reactive silicate; TP, total phosphorus; TN, total nitrogen.

Parameter	Inner Section	Central section	Outer section	Whole lagoon
Salinity	30.1±3.0 ^c	33.5±2.7 ^b	35.98±1.43 ^a	33.4±4.4
DO (mg/L)	3.5±1.8 ^a	3.5±1.7 ^a	3.08±1.30 ^a	3.4±2.0
DIN (µM)	40.24±30.00 ^a	32.59±22.89 ^a	15.40±8.39 ^b	27.63±28.65
SRP (µM)	0.68±0.95 ^{ab}	0.74±1.14 ^a	0.39±0.23 ^b	0.54±0.93
SRSi (µM)	23.67±22.61 ^a	21.13±19.64 ^a	9.18±9.56 ^b	16.28±21.74
TP (µM)	5.80±6.21 ^a	4.65±3.18 ^{ab}	2.91±1.70 ^b	4.20±6.54
TN (µM)	330.34±227.82 ^a	220.55±152.13 ^a	91.20±43.40 ^b	195.21±211.09

Ammonium (NH₄⁺) was the major DIN species in Laguna Larga (70%) during the entire sampling period. The inner and central sections were significantly different ($p < 0.05$) from the outer section, showing a spatial pattern (from high to low) in DIN concentrations. The maximum DIN concentration (112.23 µM) was recorded in the inner section of the lagoon in February 2013.

The fraction of organic nitrogen (N_{org}) in TN concentrations was the biggest (around 80% of all samples) (Table 2). However, TN showed the same DIN pattern in the inner and central sections (330.34±227.82 µM and 220.55±152.13 µM, respectively) without significant differences, but was different in the outer section (91.20±43.40 µM) ($p < 0.05$). For the whole lagoon, the mean TN concentration for the entire lagoon was approximately 200 µM. In January 2011, a maximum TN concentration of 1574.29 µM was recorded at site 9.

Although the mean SRP concentrations in the inner and central sections of the lagoon (around 0.70 µM) almost doubled those of the outer section (0.40 µM), no significant differences between them were recorded. The concentration of SRP for the whole lagoon was 0.55±0.58 µM. Like TN, the organic fraction of phosphorus was around 80% of TP. TN and TP concentrations were similar in the inner and central sections of the lagoon (5.80±6.20 µM and 4.65±3.17 µM, respectively), but different from the concentrations in the outer section (2.91±1.69 µM) ($p < 0.05$). The highest TP concentration was 80.04 µM, recorded at site 9 in January 2011 (the same date as the highest concentration of TN was recorded).

All the determined parameters were grouped taking into account the two climatic seasons of the region (wet and dry). The mean concentrations and their standard deviation are shown in Table 3. There were no significant differences (for all parameters) between the two periods of the study period.

Table 3. – Mean concentrations \pm standard deviation of the physicochemical parameters and nutrients determined in the whole lagoon in both climatic seasons (dry and wet) for the whole sampling period (2010–2014). DO, dissolved oxygen; DIN, dissolved inorganic nitrogen; SRP, soluble reactive phosphorus; SRSi, soluble reactive silicate; TP, total phosphorus; TN, total nitrogen.

Parameter	Dry season	Wet season
Salinity	33.0 \pm 1.9	34.0 \pm 2.3
DO (mg/L)	4.2 \pm 0.8	3.3 \pm 0.9
DIN (μ M)	32.47 \pm 20.45	19.82 \pm 22.89
SRP (μ M)	0.64 \pm 0.79	0.39 \pm 0.16
SRSi (μ M)	11.89 \pm 12.27	17.75 \pm 16.87
TP (μ M)	3.70 \pm 1.86	2.91 \pm 1.39
TN (μ M)	225.68 \pm 132.85	168.76 \pm 102.52

The DIN:SRP ratio was greater than the Redfield value (16:1) in all samplings: values ranged from 62:1 in the outer section to 114:1 in the inner section. The ratio of DIN to soluble reactive silicate (SRSi) was greater than a 1:1 ratio, showing that phosphorus and silicon were limiting nutrients in Laguna Larga most of the time.

The KTI, calculated for the whole lagoon and its sections, showed that the values of KTI were above 5 for DIN (eutrophic condition) and above 3 for SRP (mesotrophic condition). The highest values for both nutrients were recorded in the central section of the lagoon (Fig. 3).

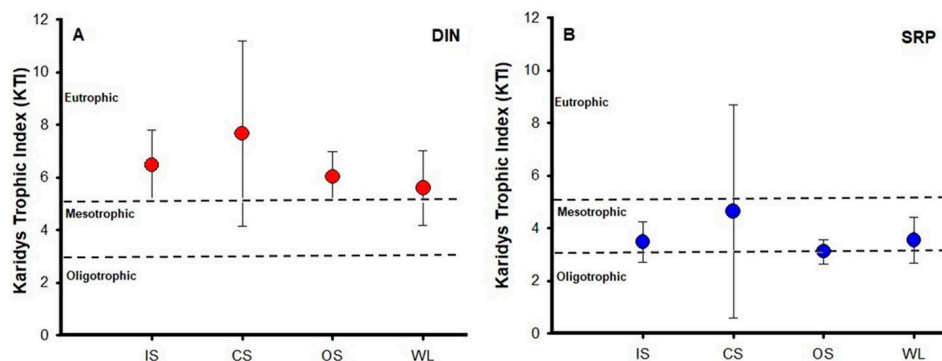


Fig. 3. – Mean Karydis trophic index (KTI) for (A) dissolved inorganic nitrogen (DIN) and (B) soluble reactive phosphorus (SRP) for each of the sections of Laguna Larga from 2010 to 2014, calculated following Karydis et al. (1983). Error bars indicate standard deviation. OS, lagoon's outer section; CS, central section; IS, inner section; WL, whole lagoon.

Temporal trends of physicochemical parameters and nutrients after restoration actions

After the actions taken to improve water exchange between the lagoon sections and the adjacent sea, water level variation (measured with a HOBO sensor) increased slightly in the inner sections of Laguna Larga. Before removal of the portion of the road that blocked water exchange between the inner section and the central section of the lagoon, the variation of water level was in the range of -0.07 and 0.09 m, and after removal the water level variation increased from -0.09 to 0.12 m (Fig. 4).

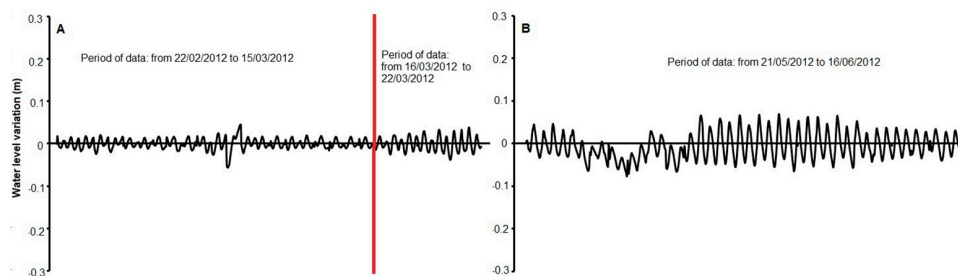


Fig. 4. – Water level variation (in m) in Laguna Larga in two periods: (A) from 22/02/2012 to 22/03/2012 and (B), from 21/05/2012 to 16/06/2012. Red line in A denotes the opening of the channel at the central section (15/03/2012)

Although the highest mean value (36.9) of salinity occurred during the restoration period (December 2012), it was not different from other salinity values in the study period (Fig. 5A). Salinity remained very stable before, during and after restoration actions. Dissolved oxygen was quite variable throughout the sampling period, and showed the greatest concentration on the same date as salinity was sampled (December 2012); however, this DO concentration was not different from DO concentrations during the rest of the sampling period. The lowest DO concentrations (from 1.5 to 2.8 mg L⁻¹) were recorded in most samplings of 2013 (after the restoration actions) (Fig. 5B). Both parameters showed a slight but significant decreasing trend ($p < 0.05$) (Fig. 6).

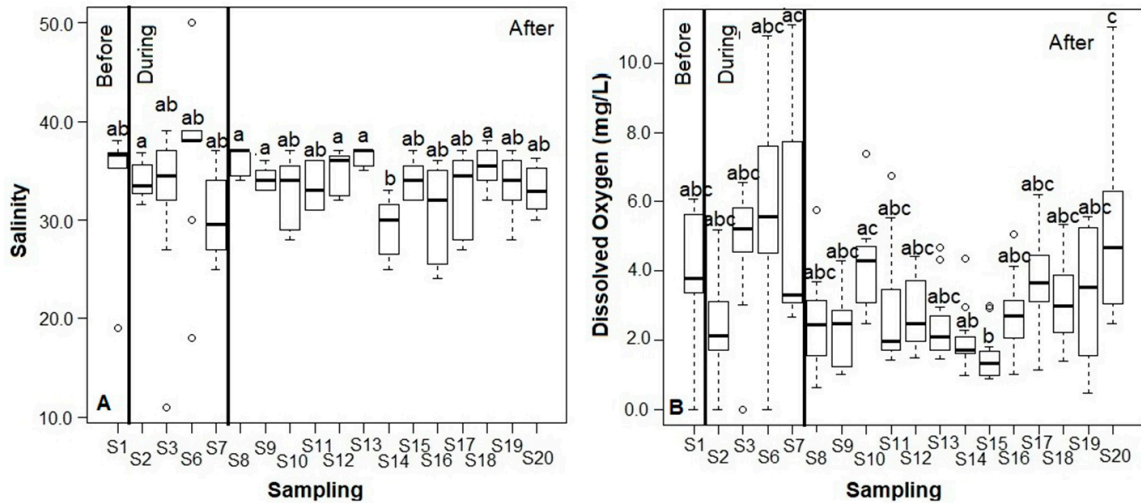


Fig. 5. – Sampling concentrations of salinity (A) and dissolved oxygen (B) in Laguna Larga between 2010 and 2014. p-values were determined according to the Kruskal-Wallis test. Different letters indicate significant differences between samplings; the box represents 50% of the data; black line inside the box is the median; dotted line ends are maximum and minimum values; circles are atypical values; confidence interval was 95%.

Except SRP, dissolved nutrients (DIN and SRSi), showed a stable behaviour during the restoration actions (Fig. 7). All dissolved nutrients had lower concentrations immediately after completion of the restoration actions, but SRP concentrations remained more stable towards the end of the sampling period than DIN and SRSi (Fig. 7). Only SRP and SRSi showed a significant decreasing trend ($p < 0.05$); DIN also showed a decreasing trend, but it was not significant ($p > 0.05$) (Fig. 8).

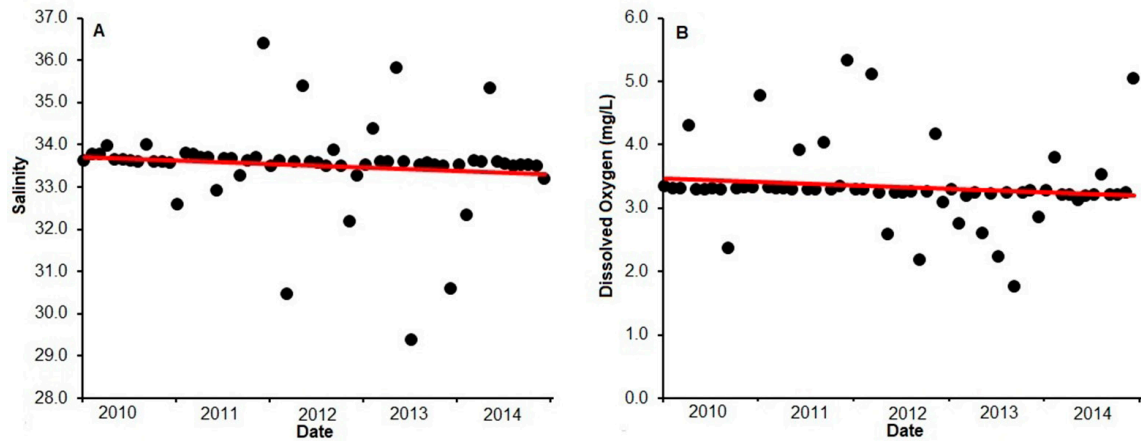


Fig. 6. – Temporal trend of salinity (A) and dissolved oxygen (B) in Laguna Larga between 2010 and 2014. Red line indicates trend.

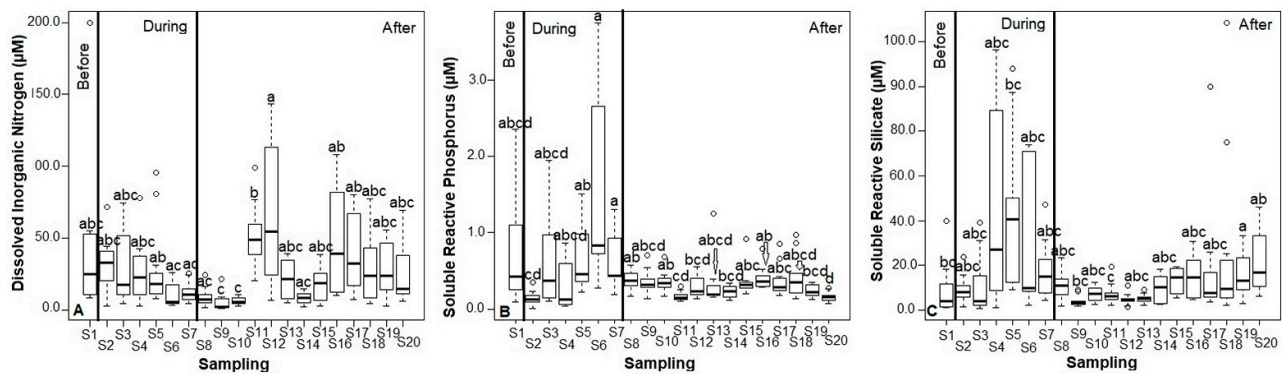


Fig. 7. – Sampling concentrations of dissolved inorganic nitrogen (A), soluble reactive phosphorus (B) and soluble reactive silicate (C) in Laguna Larga between 2010 and 2014. p-values were determined according to the Kruskal-Wallis test. Different letters indicate significant differences between samplings; the box represents 50% of the data; black line inside the box is the median; dotted line ends are maximum and minimum values; circles are atypical values; confidence interval was 95%.

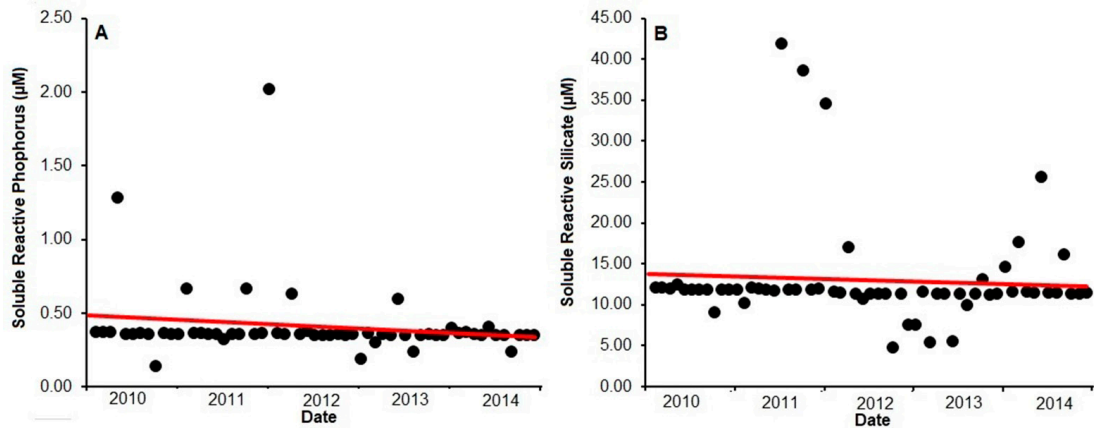


Fig. 8. – Temporal trend of soluble reactive phosphorus (A) and soluble reactive silicate (B) in Laguna Larga between 2010 and 2014. Red line indicates trend.

TN and phosphorus concentrations showed more variability during the restoration actions (Fig. 9). For both parameters, the lowest concentrations were recorded after the restoration actions, with a significant decreasing trend ($p < 0.05$) (Fig. 10).

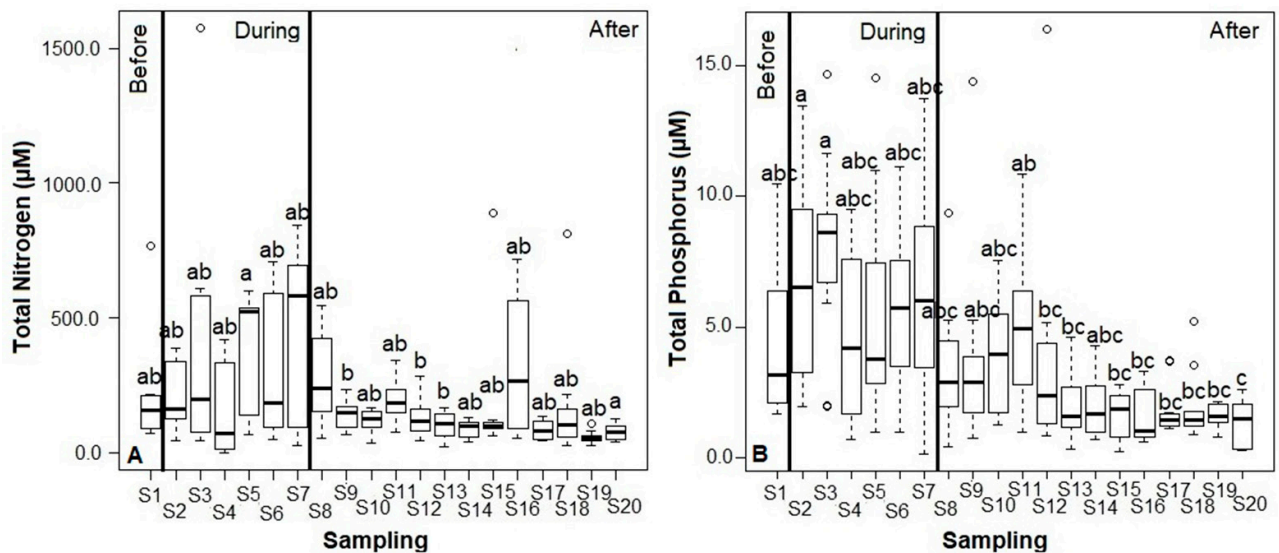


Fig. 9. – Sampling concentrations of total nitrogen (A) and total phosphorus (B) in Laguna Larga between 2010 and 2014. p-values were determined according to the Kruskal-Wallis test. Different letters indicate significant differences between samplings; the box represents 50% of the data; black line inside the box is the median; dotted line ends are maximum and minimum values; circles are atypical values; confidence interval was 95%.

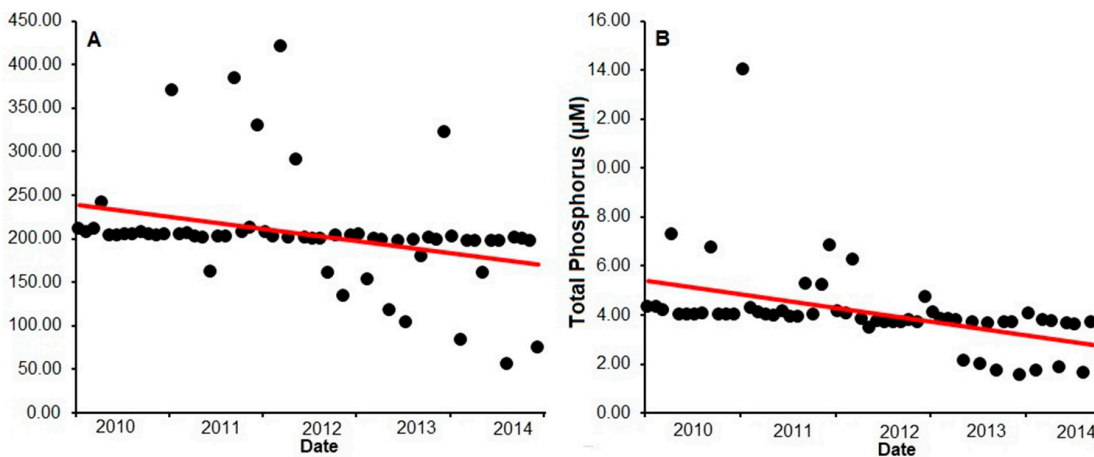


Fig. 10. – Temporal trend of total nitrogen (A) and total phosphorus (B) in Laguna Larga between 2010 and 2014. Red line indicates trend.

DISCUSSION

During the last three decades, Laguna Larga has been subjected to many anthropogenic modifications, particularly since the construction of the first hotel in Cayo Coco, in 1990. The Cayo Coco area is the second sun and beach tourist destination in Cuba, and development has continued to this day. The impacts on the lagoon—particularly on its biogeochemistry and water quality—resulting from these modifications were well-documented by González-De Zayas et al. (2018) during the 2007–2009 period and González-De Zayas et al. (2021) during the 2015–2018 period. The same authors reported that, due to the conjunction of factors (human and natural) that impact the functioning of Laguna Larga, it was not possible to determine significant differences in the biogeochemical behaviour between the climatic periods of the region. The present study was the first opportunity to assess the impact of restoration actions on the water quality of this Caribbean coastal ecosystem. Results showed that all measured parameters (except DIN) responded “quickly” and significantly to the implemented actions, and that the magnitude of changes in water quality depends on many factors, including the accumulation of historical external loads of nutrients in the waters, sediments and the lagoon morphology.

During this study, Laguna Larga showed similar ranges of salinity (from 11.0 to 50.0) as in previous studies by González-De Zayas et al. (2018) from 2007 to 2009. In the previous studies, salinity values were higher (similar to those of the adjacent sea) in the outer section of the lagoon and lower in the inner section, despite the volumes of sewage and freshwater discharged into the inner section (González-De Zayas et al. 2018). Salinity showed the same behaviour before Hurricane Irma paralleled the northern coast of the Province of Ciego de Ávila, very close to Laguna Larga, in September 2017: the mean value of this parameter was around 36.0 between 2015 and June 2017 (González-De Zayas et al. 2021). Salinity variations resulting from the restoration actions in Laguna Larga between 2011 and 2012 were slight but significant and remained over 30.0 for the whole lagoon and for each of its sections. Leruste et al. (2016) found no trend in salinity after the restoration actions in some Mediterranean lagoons that showed the same salinity regime in response to freshwater supplies and seawater exchange.

As in previous studies (González-De Zayas et al. 2018, 2021), some episodes of hypoxia (less than 3.0 mg L⁻¹) and anoxia (less than 1.0 mg L⁻¹) were recorded at Laguna Larga, particularly at site 9. This site is the main sewage discharge point and is where the lagoon has received the strongest geomorphological impact due to the hotel construction (González-De Zayas et al. 2018), resulting in the long residence time of water in the inner section (González-De Zayas et al. 2021). All the lagoon sections showed similar mean DO concentrations, but a significant decreasing trend was found, showing a slight change in DO concentration of around 0.1 mg L⁻¹ per year. For this reason, unlike results found by Newton et al. (2020) at Formosa lagoon (Portugal) and García-Barcina et al. (2006) at the Bilbao estuary (Spain), the restoration actions in Laguna Larga were not effective considering DO as an indicator.

DIN mean concentration was greater than that of a previous study conducted in Laguna Larga between 2007 and 2009 (González-De Zayas et al. 2018) but was lower than the mean DIN concentration reported by González-De Zayas et al. (2021) in the 2015–2018 period. In all the studies, mean DIN concentrations were above the concentration limit (>16.54 µM) proposed by Newton et al. (2020) to consider a Mediterranean coastal lagoon in poor ecological status. In our study, DIN concentration had a negative but not significant trend in the whole lagoon and its sections, and showed an increasing pattern from the outer to the inner section (Table 2).

In the present study, the mean concentration of TP was similar to that in Laguna Larga during the 2007–2009 period (4.6±4.6 µM) (González-De Zayas et al. 2018), but higher than that between 2015 and 2018 (2.6±1.7 µM) (González-De Zayas et al. 2021). In both studies, Torg was over 80% of TP. These mean TP concentrations are around the value reported by Leruste et al. (2016) for some hypertrophic Mediterranean lagoons with limited water exchange with the adjacent sea.

From 2010 to 2014, the trend of TP for the whole lagoon decreased significantly, with a rate of 1.45 µM y⁻¹. This change had two homogenous periods (Fig. 9), one before February 2013 and the other after this date. This behaviour showed a change in TP concentration from February 2013 that could have extended to 2017 (before Hurricane Irma) (González-De Zayas et al. 2021). However, in each lagoon section, TP showed a variable change date in the homogeneity of concentrations: the outer section responded more quickly (March of 2012) than the central and inner sections (December of 2012) to the restoration actions in the lagoon. In the outer section, the most flushed area of Laguna Larga, the biogeochemical responses are related to water residence time and water renewal capacity (Borja et al. 2010, González-De Zayas et al., 2021). In addition, water residence time in the inner section tended to be low, resulting in a eutrophic tendency in this part of the lagoon when external factors such as nutrient supplies and climate-related events were present (Mudge et al. 2008, Newton et al. 2020).

Like TP, mean TN showed a concentration like that determined by González-De Zayas et al. (2018) between 2007 and 2009 during the sampling period and the same increasing pattern from the outer to the inner section of the lagoon. However, the TN concentration recorded in this study was lower than that reported by González-De Zayas et al. (2021) from 2015 to 2018. The mean TN concentration for the whole lagoon was around the values reported by Leruste et al. (2016) for some hypertrophic Mediterranean lagoons with limited exchange with the adjacent sea. However, the TN concentration in the inner section of Laguna Larga almost doubled that of these hypertrophic lagoons.

Like TP, the trend of TN concentration decreased significantly from 2010 to 2014, breaking data homogeneity and resulting in a marked change in TN concentration for the whole lagoon in May 2012 (Fig. 5). However, this trend decreased significantly only in the inner and central sections; the change was in May 2012 in the former and in December 2012 in the latter.



Fig. 11. – Satellite images of Laguna Larga in November 2011 (A) and 2012 (B).

The trophic state of Laguna Larga, considering the values of KTI, was worse than in the 2007–2009 period. This behaviour could be due to the first restoration actions (filling of channels, removal of sediments), which helped the release of nutrients to the water column and could be cause a high primary production of phytoplankton (Leruste et al. 2016), with predominance of cyanobacteria, particularly in the inner and central sections (González-De Zayas et al. 2018). However, after the opening of the channel and the removal of obstacles and mangrove roots, the TP and TN concentrations dropped significantly, showing values lower than those reported by González-De Zayas et al. (2018) between 2007 and 2009.

Most TN and TP at Laguna Larga occurs in organic fractions; for this reason, the decrease of TN and TP concentrations could be related to a reduction in density by phytoplankton, mainly due to an increase (slight, according to water variation measured by water level data loggers) of water exchange between the lagoon sections and with the adjacent sea. Improved water exchange reduces the risk of excessive microalgal production and phytoplankton growth, thereby lowering organic nitrogen and phosphorus concentrations (Greening and Janicki 2006). Changes in water colour (associated with phytoplankton density) of Laguna Larga are shown in Figure 11. It is evident that in 2011, before the opening of the channel, the lagoon water was green, and after the opening of the channel in 2012, the water colour could be related to the colour of the bottom and the bathymetry of the lagoon.

Some authors have assessed the biogeochemical, trophic and ecological responses of coastal lagoons to implement restoration actions such as the reduction of nutrient loads (Greening and Janicki 2006, Borja et al. 2010, Leruste et al. 2016, Newton et al. 2020), and most of them agree on the fact that the recovery of the ecological functions of these lagoons after restoration actions might not occur simultaneously. In some cases, the reduction of chlorophyll, TN and TP took only two years, but the recovery of some ecological functions could take between 10 and 25 years (Leruste et al. 2016). Leruste et al. (2016) remark that recovery depends on factors such as ecological interactions between species, hydrodynamics of systems, water exchange and prior trophic conditions of the lagoon.

Although Laguna Larga is a small lagoon, it is a complex system conditioned by various factors that drive its spatial variability. With these restoration actions, this lagoon did not recover its original biotic composition and functions, and only reached alternative stable states like those proposed by González-De Zayas et al. (2018). Most of the nutrients measured showed a reduction in their concentrations, which must have enhanced the water quality of the lagoon.

This is the main reason to propose management actions such as zero sewage disposal, and the pumping of high volumes of water from the adjacent sea to increase water renewal in the lagoon.

CONCLUSIONS

The trophic state and water quality of coastal lagoons like Laguna Larga are very variable (spatially and temporally) due to natural factors such as climate and morphology and many anthropogenic actions. The spatial distribution of physicochemical parameters and nutrients measured in Laguna Larga showed the same pattern as that observed in previous studies: an increase in nutrient concentrations and an altered trophic state from the outer to the inner section, mainly conditioned by sewage disposal and limited water exchange. After the opening of the lagoon

main channel to increase water renewal in the inner and central sections, hydrodynamics improved sufficiently to increase water quality. These actions may have contributed to the decrease in phytoplankton density and in TN, TP, SRP and SRSi. Some other restoration actions (the total closure of all wastewater discharge points and pumping of seawater from the adjacent ocean) are proposed to improve the ecological functions of this coastal lagoon.

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AUTHORSHIP CONTRIBUTION STATEMENT

Roberto González-De Zayas: Conceptualization, Formal analysis, Writing – original draft. **Martín Merino-Ibarra:** Investigation, Methodology, Formal analysis, Writing – review & editing. **Julio Antonio Lestay-González:** Formal analysis, editing. **Fermín Sergio Castillo Sandoval:** Formal analysis, writing – review & editing. **Miguel Ángel Alatorre Mendieta:** Conceptualization, writing – review & editing. **Alexey Valero-Jorge:** Conceptualization, methodology, writing – review & editing.

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