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Chapter 6

The Relationship of Sediment and Intersitial Water Properties with Mangrove Health in a Subtropical Coastal Lagoon of Mexico

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Abstract

The aim of this study was to determine the influence of the physicochemical properties of interstitial water, sediment geochemistry and sediment grain size on the health of mangroves in three Basins (I, II and III) in Cuyutlán Lagoon, Mexico. Monthly sampling was conducted at eight stations from February to October 2014. The optimum reforestation conditions were observed at stations in Basin I (1A and 1B) and II (2C and 2D), where exchange of water between the ocean and lagoon predominates (Tepalcates and Ventanas Channels) and tidal influence induces water exchange that generates increased dissolved oxygen (3–4 mg/l) concentrations, low salinity (20–30) and greater coverage of healthy mangrove, with sufficient organic carbon (4–6%) for assimilation by the plants. By contrast, stations in Basin III were characterised by water stagnation resulting in increased salinity (40–50), depletion of the dissolved oxygen concentrations (0.1–2 mg/l) and low organic carbon (2%) in sediments, which contributed to low dwarf mangroves with low coverage most likely in response to environmental stress. Finally, the healthiest mangrove was found in areas where the dynamics favoured the deposition of organic carbon and medium sands in the sediment, which generated greater nutrient availability for fixation and assimilation by the roots.

Keywords: Cuyutlán Lagoon, physicochemical, organic carbon, interstitial water, sediment

1. Introduction

Coastal lagoons are considered geomorphological depressions in the coastal area less than 10 m deep, protected by physical barriers or hydrodynamic processes [1]. These coastal

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environments generally have permanent or ephemeral links with the sea and have unique physical, chemical and biological conditions resulting from the interactions of two different bodies of water [2, 3]. These ecosystems are of great economic and ecological importance due to high primary productivity and by providing areas for breeding, feeding and protection of diverse species [4].

The elevated productivity in these water bodies is related to the input of inorganic nutrients resulting from ocean-lagoon and continent-lagoon interactions, and the recycling of labile organic matter (OM) deposited in the sediments which plays a fundamental role in the formation of assailable nutrient product diagenetic processes (remineralisation) of organic matter from primary producers [5, 6]. Moreover, the particle size distribution and the proportion of organic content affect the distribution of organisms in sediments and the zonation of aquatic vegetation. In addition, based on its structure and composition, the OM accumulated in sediments can provide a record of primary productivity fluctuations in these marine environments [7, 8].

Sedimentation rates in coastal lagoons vary widely, and the type of sediments associated with these systems is considered an important ecological factor, due to concentrations of trace elements, nutrients and OM necessary for basic physiological processes of primary producers [9]. Furthermore, biogeochemical cycles in these systems are affected by geochemical processes between the sediment-water interface such as exchange and diffusion of dissolved ions and gases [10].

Mangrove ecosystems are characterised as wetlands located in tropical and subtropical coastal areas of the world and are associated with complex sedimentary environments such as estuaries and coastal lagoons. These systems are major producers of OM and serve as ecologically important protected areas and breeding and nursery grounds for many species [11–15].

The presence of mangrove communities in the coastal zone provides important ecosystem services including protection from storms surges, protection against coastal erosion by wave activity and provision of biological filters which retain and process contaminants and nutrient excess, organic matter decomposition. In addition, they act as sinks for CO_2, potentially mitigating climate change [16]. This type of wetland is characterised by halophile properties [17] that withstand wide variations in salinity and temperature in short periods of time [15]. Mangrove forests are associated with conditions such as silt-clay sediments with high accumulation of organic matter [18], sediment flooding for better propagule rooting [19] and high, constant nutrient availability [20–23].

Because of the important ecological and environmental services provided by mangroves, mitigation measures are necessary to avoid deforestation of these ecosystems, as well as restoration activities (replanting). For successful mangrove restoration, knowledge of the surface and subsurface physicochemical conditions of the sediments is extremely important. The objective of this study is to generate a baseline of physicochemical and sediment data, which will improve mangrove replanting activities in this tropical lagoon and serve as a tool to promote restoration in other similar regions.

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2. Materials and methods

2.1. Description of the study area

Cuyutlán Lagoon (19°07′ N, 104°05′ W) is located on the northeast coast of Colima, Mexico, bordered to the north by Manzanillo Bay and by Armeria River to the south. Through natural physiography and engineering activities, the lagoon system was divided into three Basins (I, II and III, **Figure 1**), with a large expanse of mangrove forest the edge of each basin, primarily consisting of *Laguncularia racemosa* and *Rhizophora mangle*. The region covers an area of approximately 7200 hectares, with a length of 37 km and a 5–6 km wide sand bar [22]. The lagoon is connected to the sea by three channels: Tepalcates, Ventanas and Tunnel [24]. The study area has a warm, humid tropical climate Aw_o type, with an annual temperature variation between 25 and 26°C. The summer rainy season begins around May and ends in October, with the highest rainfall occurring in July and September; winter has a lower rainfall of 5 mm, with an average annual rainfall between 800 and 1200 mm [25].

2.2. Field methodology

From February to October 2014, monthly sampling was carried out in three stations occupied in three basins of the Cuyutlán Lagoon, which were established based on areas of mangrove replanting. Two stations were located in Basins I and II (1A and 1B and 2C and 2D, respectively), while four stations were located in Basin III (3E, 3F, 3G and 3H). Samples were taken

Figure 1. Geographical location and reforestation areas (Basins I, II and III) analysed in Cuyutlán Lagoon, Colima, Mexico.

to determine physicochemical parameters of the sediment pore water reforested areas, during flooded and nonflooded conditions. In the nonflooded stations, a pit of 15–20 cm depth was excavated which was allowed to fill with interstitial water. For flooded stations, the measurements were made in the water adjacent to the sediment. Temperature, dissolved oxygen and salinity were measured using a mini CTD YSI Pro 2030, while the pH was measured with an Orion Star Thermo Scientific potentiometer A221.

Sediment cores were extracted manually with PVC tubes 1 m length and 4.5 cm in diameter for textural analysis (grain size, porosity and humidity) and 3 cm in diameter for chemical analysis (percent organic carbon) during February, March, May, June and August.

To establish the current health status of the mangroves, they were evaluated according to the methodology proposed by [26]. Fifteen indicators were used: leaf colouration, leaf cover, plant height, phenological aspects (flowering, fruiting, or vegetative aspect in later stages) time to reproduction (if not mature), number of propagules or reproductive structures (e.g. few flowers or a few propagules on the ground), presence of dwarfism, turgor and brilliance of leaves, stem strength, presence of pest damage, presence of salty plains, presence of marshes, diameter at breast height (DBH) of less than 10 cm and a-zonal distribution.

2.3. Laboratory methodology

The organic carbon content of the sediment was determined by the 2540G method proposed by [27], a semi-quantitative determination which consists of drying the sediment at 105°C for 3 hours, after which the dry sample is incinerated at 550°C in a Felisa FE340 muffle. The percentage organic carbon in the sediment was obtained by the weight difference in the sample using the following expression:

$$\text{Organic carbon (\%)} = \left[(\text{\%Organic Matter})/1.724\right] * 100 \quad (1)$$

Where % organic matter is equal to volatile substances in the sediments and 1.724 is the Van Bemmelen factor, which considers that organic matter contains on average 58% carbon.

The porosity of samples was obtained by determining the difference between the wet and dry samples according to [28].

$$\text{Porosity (\%)} = \text{Initial weight} - \text{Final weight} \quad (2)$$

The sediment humidity (moisture content) was calculated by the difference in the wet sample weight and subsequent drying to constant weight based on the following expression:

$$\text{Humidity(\%)} = \left[(\text{Initial weight} - \text{Final weight})/(\text{Initial weight})\right] * 100 \quad (3)$$

A descriptive analysis of the data (mean, variance and standard deviation) was performed followed by tests of normality (Kolmogorov-Smirnov and Lilliefors test) and homoscedasticity of variance (Cochran, Hartley and Bartlett test) to define whether to use parametric or nonparametric analyses. To establish the relationship of elemental chemical content with

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sediment texture, a simple correlation was performed at a significance level of $p < 0.05$, in addition to a descriptive data analysis of normality and homoscedasticity to establish possible differences between sampling stations.

3. Results

The mean concentration of interstitial salinity in mangrove reforestation areas varied between 25 and 30 during the study (**Figure 2**). The highest salinity values were recorded in Basin III (3E, 3F, 3G and 3H) stations, with minimum of 5 and maximum of 45–50. On the other hand, stations in Basin I (1A y 1B) recorded minimum 12 and maximum close to 40, and the same pattern was observed in Basin II (2C y 2D) stations with minimum values of 10 and maximum of 35. Spatially, the widest range of salinity was detected in Basin III, while Basin II showed the least variation in values. Temporally (**Figure 2B**), the highest salinity concentrations were recorded during the months of April (41), May (39) and June (34), gradually decreasing until September (10); months were significantly different ($p < 0.05$). In the dry season, salinity reached the highest average (35), with a range from 10 to 50; on the other hand, during the rainy season, the average salinity was 24 (range 5–38). The seasons were significantly different ($p = 0.00$).

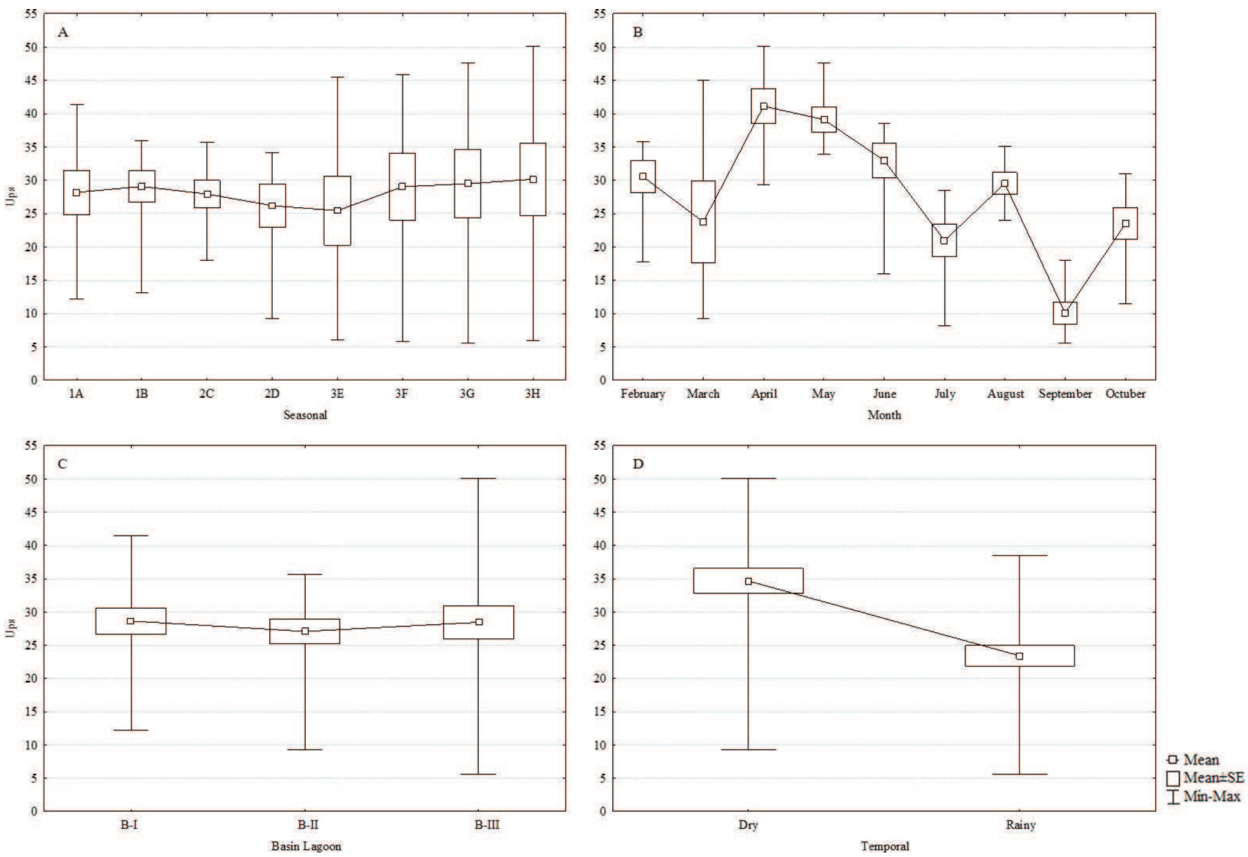

Figure 2. Seasonal (A), monthly (B), spatial (C) and temporal (D) variation of the salinity in interstitial water on reforestation zones of Cuyutlán Lagoon.

The average temperature obtained in the areas of reforestation was 29–30°C. The largest temperature fluctuations occurred in station 1A (Basin I) with min of 25°C and max of 35°C. At the remaining stations, temperatures did not exceed 32°C. There were no significant spatial differences in temperature evident in the replanted areas ($p > 0.05$) (**Figure 3A**). Monthly variations in temperature demonstrated significant differences ($p < 0.05$), with the highest temperature fluctuation in March from 25 to 35°C. A significant increase was recorded in May, which oscillated between 28 and 31°C until October. Low temperatures were obtained in February and April, with significant differences ($p < 0.05$) (**Figure 3B**). Spatially, Basin I showed the greatest variability in temperature, with a maximum of 35°C, while the minimum of 24.3°C was recorded in the Basin III (**Figure 3C**). Significant differences in temperature ($p < 0.05$) were recorded between the rainy season (mean of 30°C) and dry season (mean of 24°C) (**Figure 3D**).

The mean values of interstitial dissolved oxygen concentrations registered in the stations in Basins I and II ranged between 2 and 4 mg/l (**Figure 4A**), while in Basin III, the average values ranged between 0.1 and 2 mg/l. The greatest fluctuations were recorded at stations 1A and 1B, both with a minimum of 0.1 mg/l and maximum values of 8 and 10 mg/l, respectively. The maximum values in Basin III did not exceed 2 mg/l. Dissolved oxygen concentration in Basin III was statistically different from those recorded Basins I and II ($p > 0.05$). Monthly records showed an increase in dissolved oxygen concentrations in May (4 mg/l), a significant variation compared to previous months (February, March and April), which had lower values (range 0–0.1 mg/l).

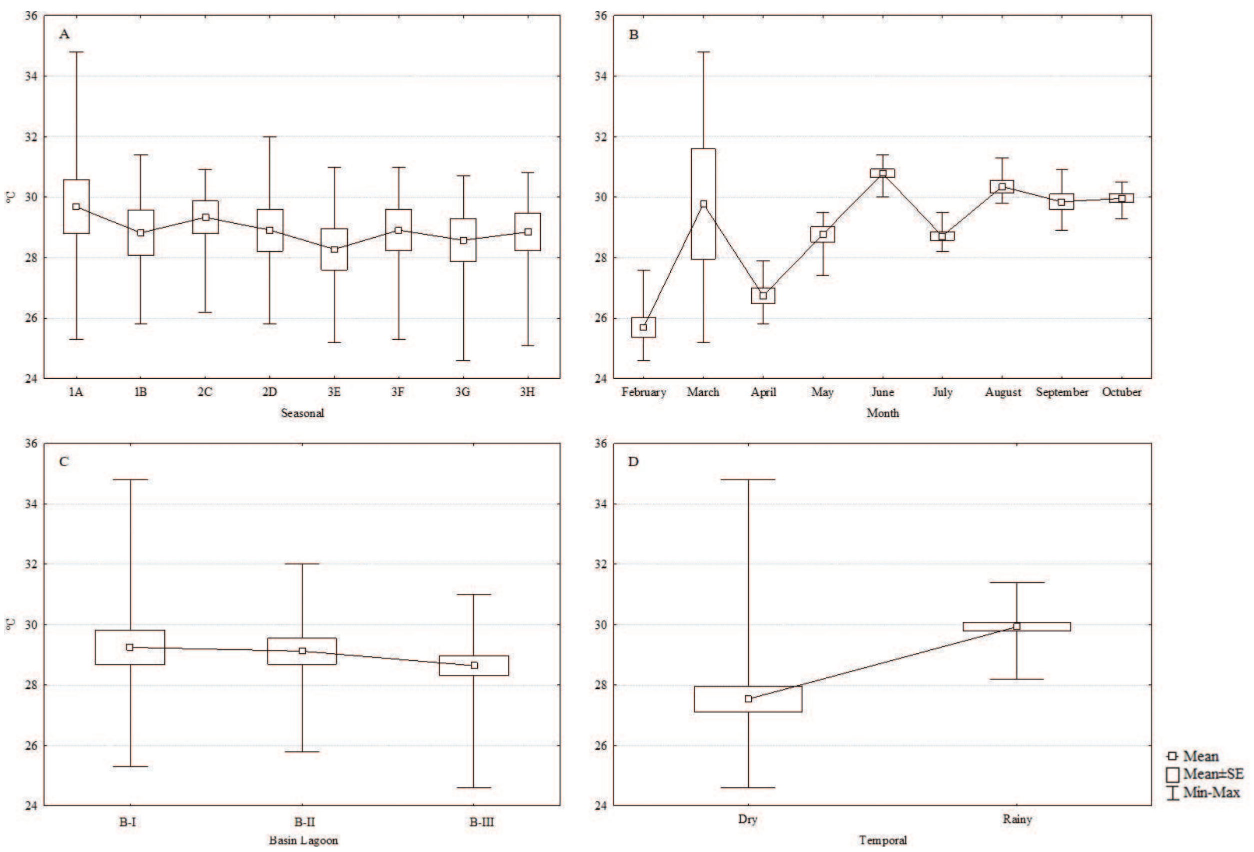

Figure 3. Seasonal (A), monthly (B), spatial (C) and temporal (D) variation of the temperature in interstitial water on reforestation zones of Cuyutlán Lagoon.

September showed the highest fluctuations, with a minimum of 0.1 mg/l and maximum of 10 mg/l (**Figure 4B**). Statistically, there were no significant differences in dissolved oxygen concentrations between February, March and April ($p > 0.05$). Basin III presented low oxygen concentration with an average of 0.2 mg/l, whereas Basins I and II maintained an average between 2 and 4 mg/l (**Figure 4C**). No significant seasonal differences occurred; however, the oscillations were highest during the rainy season (min = 0.1 mg/l; max = 10 mg/l) (**Figure 4D**).

The pH interstitial values showed no statistically significant variation between stations ($p > 0.05$). On average, pH values ranged from 7.8 to 8.1 and demonstrated no significant spatial patterns ($p > 0.05$). Similarly, there were no significant differences in the pH values between the months of February to April ($p > 0.05$). Station 1A registered a pH minimum of 7 and maximum of 8.6, whereas in station 1B, the minimum was 6.9 and maximum 9.1 (**Figure 5A**). Monthly values were homogenous between February and April, averaging 7.7. On the other hand, pH increased significantly to 8.3 in May ($p < 0.05$). Values decreased from May to July, until reaching the minimum value recorded in the study (7.2). Thereafter, the values progressively increased until October (8.4) (**Figure 5B**). Spatially, the different basins (**Figure 5C**) did not register a significant difference ($p > 0.05$); nevertheless, Basin I showed greater pH variation, with minimum values of 6.9 and maximums of 9.1. In Basins II and III, pH values on average ranged between 7.0 and 8.4. Finally, there were no significant differences between seasons; nevertheless, greater pH variability was observed in the rainy months (**Figure 5D**).

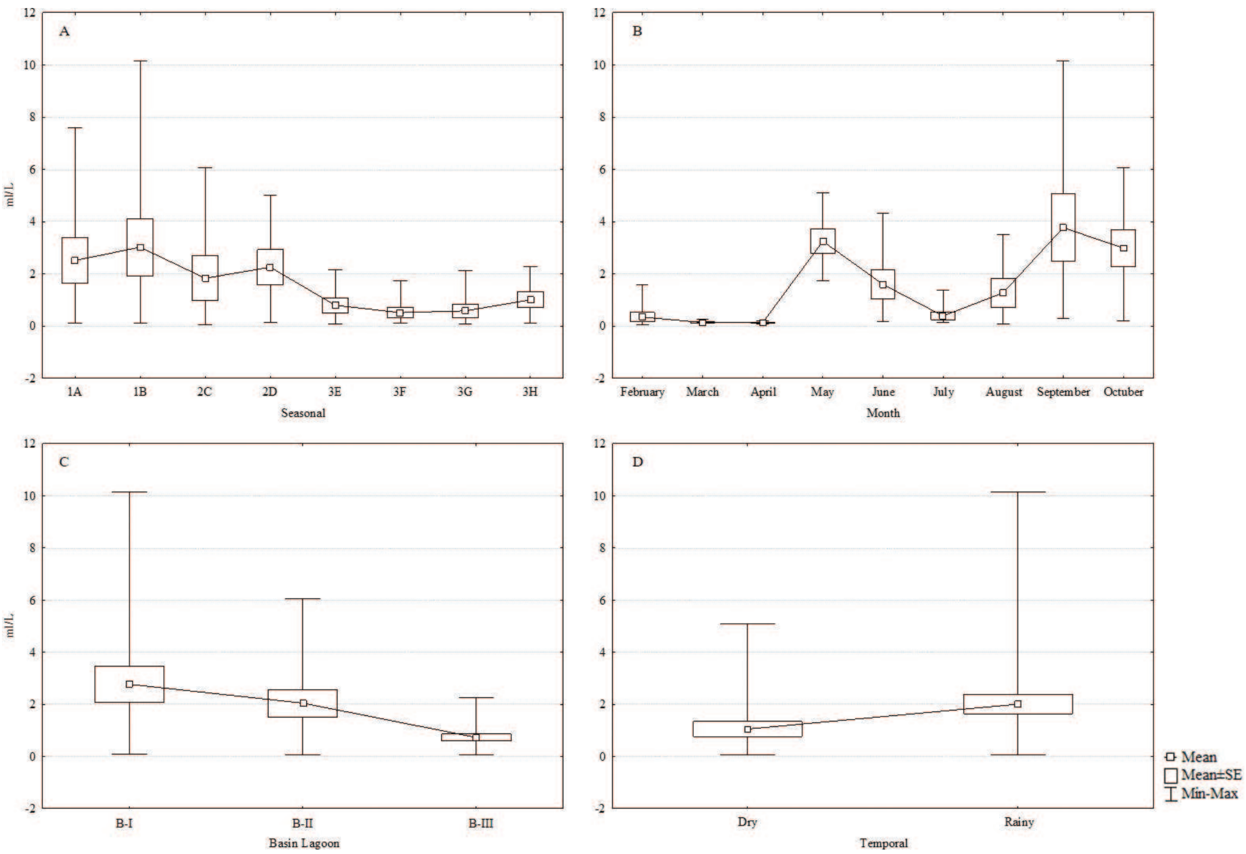

Figure 4. Seasonal (A), monthly (B), spatial (C) and temporal (D) variation of the dissolved oxygen in interstitial water on reforestation zones of Cuyutlán Lagoon.

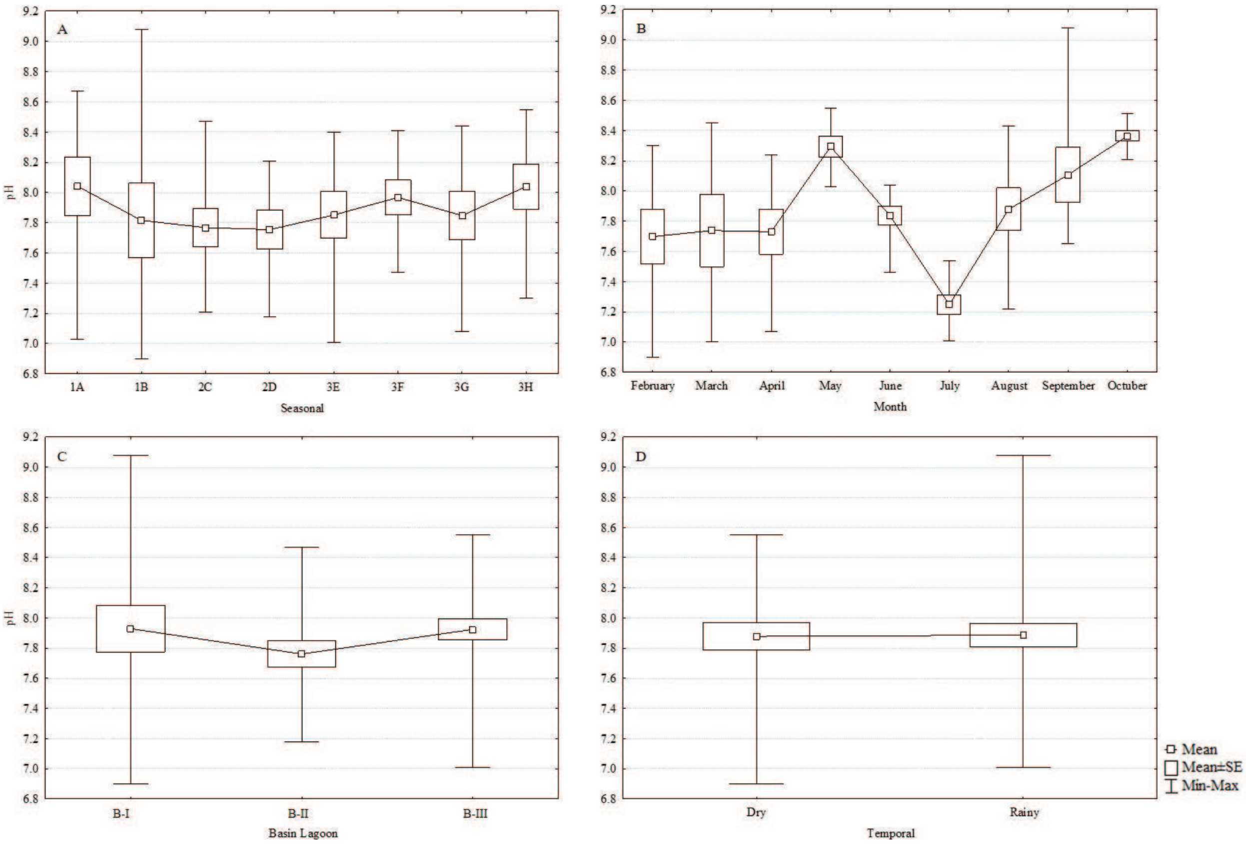

Figure 5. Seasonal (A), monthly (B), spatial (C) and temporal (D) variation of pH in interstitial water on reforestation zones of Cuyutlán Lagoon.

With regard to the percentage organic carbon (OC), the highest values during the sampling period were recorded stations 1A, 1B, 2C, 2D and 3E. On the other hand, the months with the highest OC content on average were March (5.9%), May (5.6%) and August (5.5%) (**Figure 6B**). In February, the maximum value was obtained in station 1B (7.7%) and the minimum at station 3H (1.6%) (**Table 1**, **Figure 6A**). In March and May, the maximum concentrations were observed in stations 1A, 1B and 2D with average values of 6.5%, while the minimum values were recorded in station 2C with 3% (**Figure 6A**). In June and August, high concentrations were recorded in Basins I and II (7.7% and 5.9%), while in Basin III, percentages were relatively low (2.7% and 3.2%). In general, Basin I showed higher organic carbon content (7.2%) in the reforestation zones compared to Basin III (3.8%) (**Figure 6C**). There were no significant temporal differences in the percentage organic carbon in the sediments evident during the investigation ($p > 0.05$) (**Figure 6D**).

Table 1 shows the mean values obtained from the textural analysis (grain size, porosity and humidity) and the organic carbon content of the sediment. The predominant grain size during the study showed no significant spatial variations and was comprised of medium sands (MS). The sediment porosity values averaged between 1.2 and 1.4 at stations in Basin I (1A and 1B). At those stations in Basins II (2C and 2D) and III (3E, 3F, 3G and 3H), the mean porosity values were lower and ranged between 0.4 and 0.8. Humidity showed a significant variation between the stations ($p < 0.05$). During February, the humidity was between 58.9 and 65.8% (**Table 1**), which decreased to 30.2% in March in Basin I, while in Basin II, higher percentages were preserved (78.1%). In May, this pattern continued with low humidity values in Basin I and high values in Basin II. During June, the humidity values showed the same behaviour obtained in February,

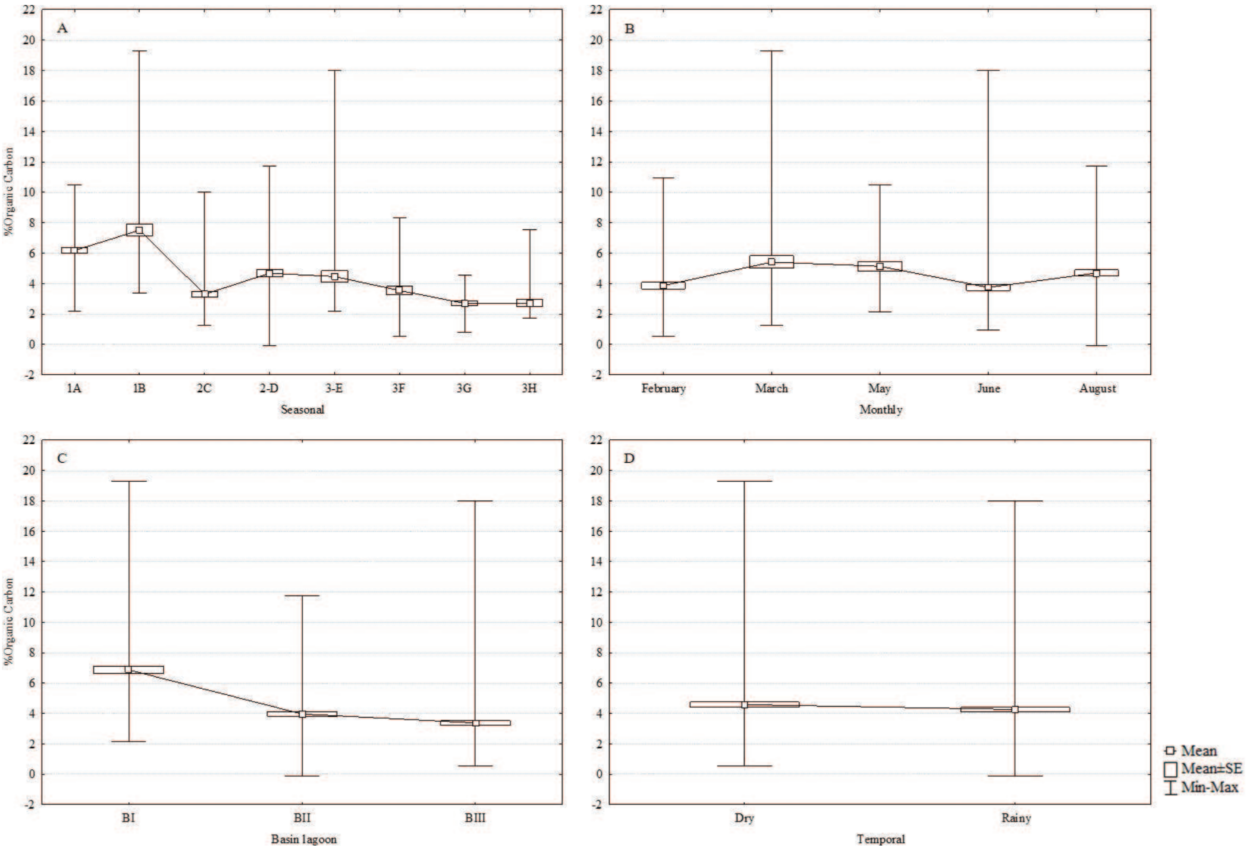

Figure 6. Seasonal (A), monthly (B), spatial (C) and temporal (D) variation of organic carbon content in sediments of Cuyutlán Lagoon.

with high values in all the stations. The maximum percentage obtained was found in station 3H with 71.6% and the minimum in station 2D with 62.5% (**Table 1**).

In the replanting zones in the Cuyutlán Lagoon, two species of mangrove were recorded in Basins I and II, *L. racemosa* and *R. mangle*, while in Basin III, only *L. racemosa* was recorded. In 2012, mangrove health was classified into three types: weak, vigorous and very vigorous. In Basin I, no results were obtained due to the lack of mangroves in the study areas. However, in Basin I, the mangrove was classified as vigorous in the southern area, while the northern area growth was deemed to be weak. Basin III mangroves were in a vigorous to very vigorous state in the areas near the shore (both in the north and south of the lagoon).

Throughout the investigation (2015), an evolution of the mangrove ecosystem was observed in each of the replanting zones of the Cuyutlán Lagoon. At those stations in Basin I (1A and 1B), the mangrove was classified as vigorous with an initial reproduction process, so that the height of the forest in these stations was between 2 and 2.5 m, maintaining a very full and extensive coverage. Similarly, at Basin II (stations 2C and 2D), a very vigorous mangrove forest was also observed with mangrove heights of between 2.5 and 4 m which were in an advanced reproduction state. It is worth mentioning that at these stations, the greatest coverage and suitable mangrove growth were observed. By contrast, the mangroves in Basin III, particularly at stations 3F, 3G and 3H, were characterised as shrub growth and excessive salt secretion. To the contrary, station 3E presented optimal growth with the mangrove classified as vigorous.

Date	Parameter	Station							
		1A	1B	2C	2D	3E	3F	3G	3H
February	% organic carbon	6.940	7.692	3.365	4.423	4.036	2.727	1.653	1.598
	Textural group	MS	MS	MS	MS	MS	MS	MS	MS
	Porosity (%)	1.281	1.2880	0.702	0.771	0.844	0.715	0.583	
	Humidity (%)	62.61	62.74	65.86	62.47	58.91	65.17	71.63	
March	% organic carbon	6.057	8.902	2.050	5.669	Dry	Dry	Dry	Dry
	Textural group	MS	MS	MS	MS	–	–	–	–
	Porosity (%)	1.433	1.327	0.447	0.958	–	–	–	–
	Humidity (%)	30.39	35.26	78.12	55.53	–	–	–	–
May	% organic carbon	7.594	6.962	4.127	3.252	Dry	Dry	Dry	Dry
	Textural group	MS	MS	MS	MS	–	–	–	–
	Porosity (%)	1.409	1.381	0.826	0.891	–	–	–	–
	Humidity (%)	34.1	34.98	58.89	57.76	–	–	–	–
June	% organic carbon	5.053	5.906	4.210	3.177	4.114	2.846	3.247	2.718
	Textural group	MS	MS	MS	MS	MS	MS	MS	MS
	Porosity (%)	1.463	1.457	0.827	0.937	0.733	0.763	0.723	0.623
	Humidity (%)	66.56	65.47	62.5	57.61	66.27	64.94	67.17	71.62
August	% organic carbon	5.858	7.692	2.941	5.608	5.212	5.113	3.247	2.718
	Textural group	MS	MS	MS	MS	MS	MS	MS	MS
	Porosity (%)	1.381	1.317	0.534	0.858	0.458	0.458	0.723	0.623
	Humidity (%)	32.91	35.75	73.89	60.16	79.08	85.92	67.17	71.62

Table 1. Monthly results of organic carbon, textural group, porosity and humidity of the sediments in the different mangrove replanting areas of Cuyutlán Lagoon (MS = Medium sand).

4. Discussion

The reforestation zones showed a marked seasonal variation in the physicochemical variables during the study. Salinity in Basins I (1A and 1B), II (2D, 2C) and III (3E, 3F, 3G, 3H) were highest in summer (April-August), before the onset of the rainy season in September and October contributed to decreased values [29]. During the summer months, the volume of water inside the lagoon was reduced, and no sediment rinsing occurred causing an excessive accumulation of salts on the surface and generating dehydration in the plants, which is associated with biological stress. It has been reported that some mangrove species are not tolerant to elevated salinity or to desiccation conditions, which causes them to weaken and reduce competition against other vascular plant species [30]. Also, due to the high evaporation rates in this period, there is an increased availability of dissolved metallic cations, which are absorbed from the sediment by the roots of the mangrove. Once absorbed, these cations can cause enzymatic inhibition, generating

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physiological stress, reduced growth and even desiccation (death) when drought conditions prevail [31]. On the other hand, the tidal level also influences sediment rinsing and with it removal of the excess salts that accumulate in the sediment or in the roots due to evaporation or evapotranspiration of the silt, as has been reported by [32]. Therefore, the high tide level is an important factor inhibiting e salt accumulation in the sediments of mangroves.

The highest temperatures in the reforested zones occurred from June to October which could be attributed to the climatic variability of the region as it coincides with the hottest months and with the onset of the rainy season [25]. During this period, the sediments are exposed to wide temperature (26–35°C) variations between day and night, in addition to decreased water column height, exposing surface sediments to a higher incidence of solar radiation. These variations were recorded at Basin III (3E, 3F, 3G, 3H) stations, with the highest temperatures recorded during June to October. On the other hand, the temperatures were lower in stations of Basins I and II (1A, 1B and 2C, 2D), due to substrate flooding by the tidal processes which promote water exchange through the Tepalcates and Ventanas Channels. In addition, the tide level is an important factor in the Cuyutlán Lagoon; generally, high-water levels occur in the winter months, decreasing in April due to the spring tides [33] influencing the temperature variations in the lagoon system substrate. Ref. [34] studied the dynamics of mangroves in Portete Bay (Cuba) and reported that temperature contributes to the zonation of different (plant) species of mangrove in coastal ecosystems, while Ref. [35] indicated that the temperature inside these systems (lagoons or estuaries) is an important factor at the physiological level, regulating growth, photosynthetic processes, respiration, and salt segregation from the organism. On the other hand, Ref. [36] reported that the incidence of radiation is a determining factor for the growth of mangrove ecosystems.

The mangrove reforestation zones showed marked differences in physicochemical parameters ($p < 0.05$) between basins; in general, low oxygen concentrations were observed in Basin III (3E, 3F, 3G and 3H), while elevated values were recorded in Basins I and II (1A, 1B and 2C, 2D). High concentrations of dissolved oxygen were recorded during August to October (mean 3.4 mg/l) associated with water exchange with the Pacific Ocean through the Tepalcates and Ventanas Channels. In addition, rainfall and fluvial contributions to the lagoon generated sediment turbulence, atmospheric aeration, and a subsequent diffusion towards the interior of the sediments [25]. Therefore, the oxygen concentrations of interstitial waters in Basins I and II are associated with circulation mediated by tides [37], which causes turbulence and resuspension of the sediments. In the internal stations of Basin III, no direct influence of the tide was registered and low values of dissolved oxygen were observed. Ref. [38] carried out a work in the bay of Matanzas, Cuba, which reported how the dynamics and topography associated with the bay influence the high concentrations of oxygen because they determine the penetration of the tide and thus the exchange of surface water.

The pH in the interstitial waters of the reforestation zones ranged from 7.7 to 8.4 in the three basins during the study. Low values of pH in in sediments can be attributed to the high amounts of organic matter, which, when decomposed, generate fatty acids and release ions H^+ that are absorbed by the sediments. On the other hand, basic conditions are generally caused by the increase of salts in the sediments which favours the formation of oxidrile ions (OH^-) [39]. Ref. [40] attributed the degradation of organic material in mangrove sediments to intermediate pH values (7–7.5). This increases nutrient availability, because the redox potential of the sediments can increase to positive values (typical of anoxic systems), favouring the presence of organisms associated with mangrove communities, such as polychaetes and bivalves. The activity of these organisms generates diffusion and water exchange, which helps maintain an adequate pH for these species (7–7.5) and results in positive cyclic oxic conditions for the ecosystem.

All the reforested mangrove sampling sites presented variable OC percentages associated with sediment depth. The elevated percentage of organic carbon at the surface can likely be attributed to the high contributions of leaf litter. After accumulation, the remineralisation of the matter generates the formation of new organic compounds, which in turn promote the early diagenesis and later migration of labile OM towards the deep sediments [41, 42]. The increase in organic carbon in the first 5 cm of sediments in Basins I and II could likely be attributed to high rates of sediment accumulation (with high organic matter content) registered in these zones which is influenced by the connections with Manzanillo Bay (Ventanas Channel) and the Pacific Ocean (Tepalcates Channel), respectively [25]. In addition, water from anthropogenic activities and runoff carry new sedimentary material, which rapidly remineralises with the recently deposited organic matter, promoting carbon accumulation below the most active diagenetic zone. Otherwise, the vertical profile shows a decrease of organic carbon through the sedimentary column, which can be interpreted as a characteristic process, because in sediments with high interstitial water flow, carbon is highly remineralised into carbohydrates and lignin [25]. Ref. [43] mentioned that the decreases of the organic carbon are due to a process of bacterial degradation of the first order, which quickly degrade the organic compounds by means of the available oxygen.

Ref. [44] observed that the percentages of organic carbon are negligible at depths of 30–90 cm due to their degradation in the presence of dissolved oxygen. This pattern was seen in Basin III stations, which had a 30% reduction of organic carbon in the first 5 cm. Ref. [45] suggested that the presence of organic carbon in sediments associated with mangroves controls the variations of the physicochemical parameters (salinity and pH) in the sediment column, due to the leachates that are generated. In this work, percentage organic carbon (2–15%) in the sediment is in the range reported by [46] in the most important mangrove ecosystem of the Gulf of Mexico (Tabasco). This suggests that the diagenetic process found in this system is in agreement with the availability of organic material and the sediment stability of a tropical coastal system.

The predominance of the MS fractions at the sampling points where there was no mangrove reforestation can in all likelihood be attributed to the sediment runoff, due in the first instance to the direct contact between the stations with the sandbar that divides the lagoon from the Pacific Ocean, and in the second, the proximity of the Basin II to the Tepalcates Channel which promotes the accumulation of inorganic sedimentary material by the high hydrodynamics associated with this area [25]. Similarly, the effect of the terrestrial runoff into the lagoon is a determining factor for the accumulation of these sediment fractions. Similar trends have been reported by [5] who found that MS and coarse sands predominate in areas with greater dynamics; while Ref [47] conclude that the topography favours distribution, because coastal lagoons with greater depth favours the presence of fine inorganic sediments and in shallower areas, thicker sizes (coarse sands). Regarding the relationship between grain size and mangrove growth, Ref. [16] mention that in these ecosystems, the main sedimentary composition associated with the best development of the mangrove are fine sediments (silt-clays) that favour the accumulation of more material organic, avoiding its early degradation, contrary to sediments that generate interstitial water penetration and therefore, a high rate of degradation of accumulated organic matter.

In the coarse sand sedimentological fraction, the dominant factor contributing to the variation in e porosity was the biogenic composition (bioclasts), which generated high porosities. At depth, the MS fraction dominated favouring a smaller interstitial space between the sediments. On the other hand, the stations of Basin III (3E, 3F, 3G and 3H) show homogeneity in the sedimentological fractions (MS) so they have relatively low porosities, this pattern can be attributed to the benthic vertical flow within the sediments. Ref. [25] demonstrated that the accumulation of new sedimentary material compacted the deeper sediments resulting in elevated porosities only in the upper surface layers. This was observed at the stations of Basins I (1A and 1B) and II (2C and 2D) during February where flooding and proximity to urbanised areas, which contributed to new anthropogenic material with coarse size due to continental runoff, increasing interstitial spaces; and the second is related to the contribution of mangrove organic matter and remains of organisms that lead to the accumulation of organic carbon in the form of coarse particles that increase the porosity values of the sediments.

The humidity content of sediment is directly related to the grain size and high porosities, since if the interstitial spaces are larger in the sedimentary column, the accumulation of water is favoured, which favours the diffusive flow of compounds and the degradation of organic matter caused by the presence of oxygen availability to carry out this process. While low humidity content with high porosity are related to the level of tide and the thickness of the water layer above each site, which generates sediments with low or high-water contact affecting the flow inside the sediments. This process was observed in the seasons of Basins I (1A and 1B) and II (2C and 2D) during the month of March where the tide level was low; however, high porosities and low moisture content were recorded.

5. Conclusions

Two principal factors which influenced the physicochemical parameters that support ideal ranges for mangrove development are the morphology of the study area and tidal levels. The decrease in OC with depth relates to bacterial remineralisation which uses the dissolved oxygen resulting from interstitial water exchange; low OC is a stressor for nutrient uptake and, in turn, reduces growth in these types of plants. Mangroves in areas with more favourable hydrodynamics conditions and physicochemical parameter stability, such as those recorded in Basins I and II, were found to be in a better overall condition after replanting. Basins II and II are therefore feasible areas for the conservation of these ecosystems, as opposed to Basin III, where dwarfism (weak mangrove) was registered. Finally, the ecological importance of mangrove ecosystems as filters that increase nutrient concentrations and other sources of organic matter was confirmed.

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