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Mangrove health in an arid environment encroached by urban development—a case study

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Abstract

Urban development will soon encroach upon several protected and largely unspoiled arid climate mangroves ecosystems located along the lagoon called Ensenada de La Paz in Baja California Sur, Mexico. Many of these mangroves are located on a large sandbar that separates the lagoon on the south side from Bahía de La Paz to the north. A general evaluation of the current status of these mangroves was conducted to establish biological and physicochemical indicators of the health of these mangroves to serve as a natural or predevelopment baseline in future management. The following parameters were measured in the feeding channels of the mangroves and at the mouth of the channels: vegetation coverage, species and health, and levels of dissolved oxygen, pH, salinity, total nitrogen, ammonium, nitrates and nitrites, phosphorus ions, and organic matter in sediments and seawater. The microbiological elements that were studied included aerobic bacteria, N_2-fixing bacteria, inorganic phosphate solubilizers, coliform, and phytoplankton diversity. Bird populations were counted, with special attention to migratory and resident birds and protected and endangered species. A comprehensive analysis of all the elements indicated that the health of the sandbar mangrove populations is good despite the proximity of a modest urban center. It also demonstrated that several biological and physicochemical parameters used in this study, including the birds, can serve as indicators of mangrove health and as a baseline for future management of mangroves in regions with arid climates.

Keywords: Benthic microflora; Biological markers; Diatoms; Migratory birds; Nitrogen fixation; Phosphate solubilizers; Phytoplankton; Sediment

1. Introduction

Mangrove ecosystems, the common intertidal ecosystems of most tropical coasts, are under severe pressure worldwide. In the last 20 years, more than

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50% of the world's mangroves have been destroyed, mainly because of clearing for aquaculture, rice cultivation, timber production, or urban development (Holguin et al., 2001; Primavera, 2000a,b; Primavera et al., 2004). Although mangrove wetlands in Mexico were protected against direct exploitation, the law has been repealed and the country has lost about 70,000 ha of mangroves between 1993 and 2000 (SEMARNAT, 2003). At the current rate of destruction, the world's mangroves will disappear in about 50 years (Ronnbäck et al., 1999). This will impose significant losses to coastal fisheries and bird life because mangroves are one of the three most productive ecosystems on a global scale, along with coral reefs and rain forests. They provide breeding grounds, refuge, food, and shelter for numerous economically and ecologically important marine species, and serve as major bird sanctuaries (Rönnbäck, 1999; Rönnbäck et al., 1999; Whitmore et al., in press). Every hectare of mangroves in Mexico produces about 750 kg per year of fish, shrimp, and shellfish for the nearby coastal fisheries (SEMARNAT, 2003). In addition to their role in supporting marine life, mangroves are important breeding and foraging areas for birds, and provide protection against predators and stopovers along migration routes. Mangrove support large numbers of insects, some reptiles, small mammals, and many invertebrates (Flores-Verdugo et al., 1990, 1992; Tovilla, 1994), improve seawater quality (Flores-Verdugo et al., 1990, 1992) by absorbing contaminants (Tam and Wong, 1995) and runoff sediments and act as a barrier for coastal protection, e.g. rise in sea level, storm surges, and possibly against some tsunamis. The success of mangroves, especially in arid and semi-arid tropical areas, is based on efficient nutrient recycling within the ecosystem, giving it abundant resources in a land where resources are scarce (Holguin et al., 2001).

Despite the plight of mangrove ecosystems worldwide, established biological and physicochemical indicators of health or danger to mangrove ecosystems are rare, making legally mandated environmental impact studies of future urban developments a difficult and unreliable task.

The La Paz region in Baja California Sur, Mexico lost 44 ha of mangrove forest between 1973 and 1981 (Mendoza et al., 1984). Our study included several undamaged mangroves located on the lagoon side of a large sandbar at the southern end of the Bahía de La Paz. These mangroves face south to the city of La Paz and some are farther west toward the foot of the sandbar. The larger Bahía de La Paz area has one of the two most important concentrations of mangroves on the Baja California Peninsula and is close to the northern limit of mangroves on the Pacific side of the North America. A residential and tourist development, including golf courses and a large marina, is scheduled for construction on the sandbar in the near future.

Mangrove ecosystems in arid climatic environments are generally nutrient deficient, especially in nitrogen and phosphorus, but at the same time are highly productive (Holguin et al., 1992). This paradox can be explained by very effective nutrient recycling that conserves them within the system. Intense and diverse microbial activity in mangroves, including N_2-fixing and phosphate-solubilizing microorganisms, is responsible for retaining the scarce nutrients within the system, and that restoration of these tropical ecosystems depends on the health of the microbial benthic communities and conservation of their geochemical environment (Alongi et al., 1993; Alongi, 1994; Holguin et al., 2001).

This study established microbial, physiochemical, and bird life indicators of the health of largely undisturbed arid climate mangrove ecosystems after performing a detailed diagnosis of biological, chemical, and physical factors. This information is intended to serve as a baseline for long-term monitoring of arid climate mangrove ecosystem health and provide quantitative tools for monitoring similar mangroves.

2. Materials and methods

2.1. Study area

The study area was part of a small mangrove ecosystem consisting of numerous patches that cover much of the shore of the sandbar that separates the Bahía de La Paz and the Ensenada de La Paz. The ensenada is 50-km^2 lagoon (24°08′N, 110°23′W) fronting the city of La Paz in Baja California Sur, Mexico (Fig. 1). The separation between the lagoon and the bay is a sand spit or bar called "El Mogote". Currently, the study area has very light urban pressure,

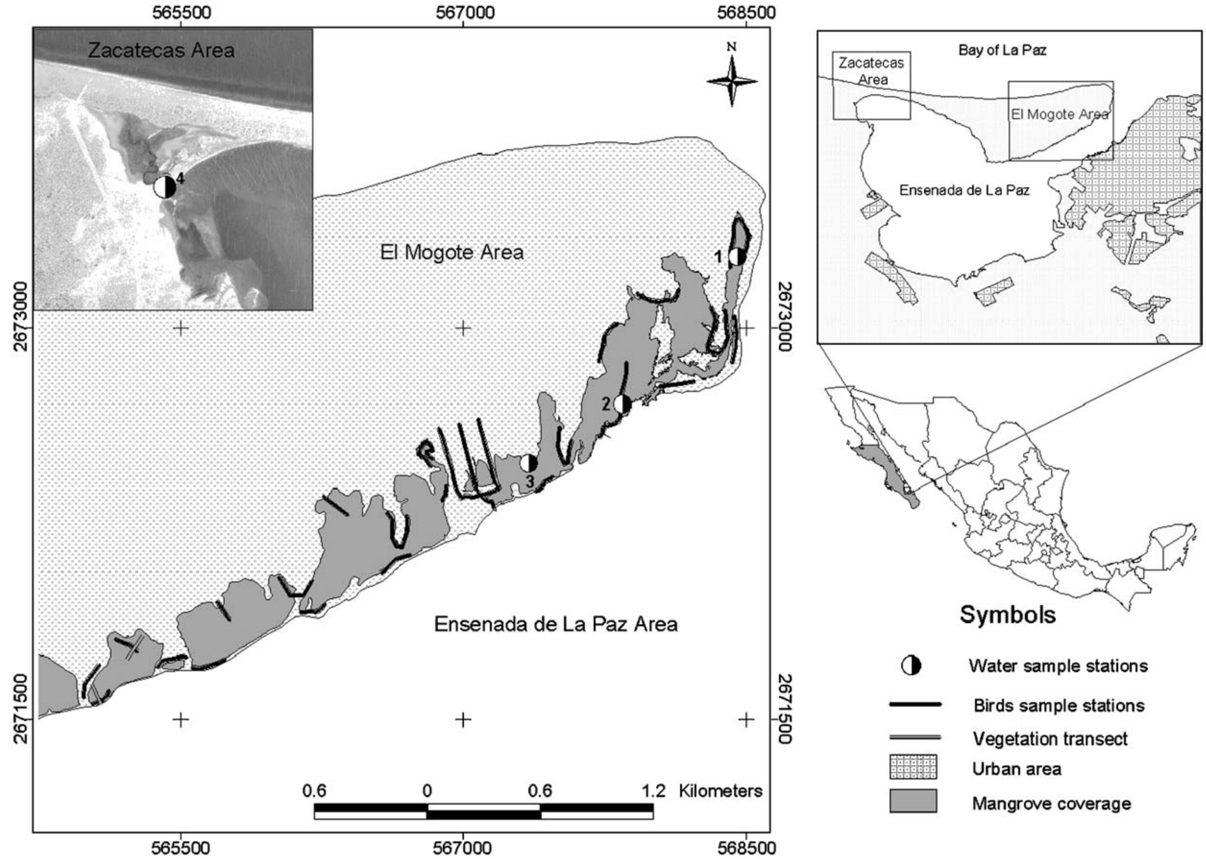

Fig. 1. Study area around the Ensenada de La Paz and station locations. Samples for microbial and chemical analyses were collected from Stations #1 to 4. Detailed floral analysis was done along the two transects and bird counts were taken at the marked stations.

with only a few weekend visitors, some small scale fishing by a few local artisanal fishermen, minor ecotourism and marine sports, and somewhere between 50 and 100 year-round sailboat residents anchored in the lagoon. During summer hurricanes, occasional overflow from the municipal wastewater treatment plant enters the lagoon. On the whole, these mangroves are nearly pristine, considering their proximity to a city of approximately 250,000 inhabitants. The lagoon is enclosed by the bayshore and sandbar except for a 600-m navigable channel connecting the lagoon with the open bay. Eight mangrove patches located along the south shore of El Mogote were studied. These patches are relatively close to the city and on the north side of the channel. The easternmost patch is directly across the channel from the city center, only 600 m away, and the farthest west is about 1.3 km from the city center. The length of the study area of eight mangrove patches spans 4.2 km. An additional location is a large patch known as the Zacatecas area, about 9.7 km west of the city, at the foot of the sandbar, where the bar connects to the mainland. Because of its relative remoteness, this mangrove is the least affected by human activity. It is used only by local fishermen and occasionally by bird watchers (Fig. 1, site #4). This site also serves as a major nesting ground for a marine bird species in danger of extinction (see below).

2.2. Stations and sampling

For physicochemical and biological sampling, four stations were selected (Fig. 1). Station #1 was located in a naturally blocked mangrove patch containing two small lagoons (3.2 ha). Its feeding channel was blocked by a sand dune transported there by a hurricane in late summer 2001. At the time of the study (March–April 2003), these small lagoons were almost dry, and most trees appeared dead. Therefore, water samples were taken outside the entrance to the blocked channel. The regular feeding channels of the other three inspection sites were intact, and water samples from within the channel and from the channel entrance were analyzed. Birds were counted using 15 dune stations facing the mangrove and 9 stations located on the beach in front of the mangroves (Fig. 1).

Water samples were collected in 600-ml plastic bottles from a depth of 0.5 m (shallow channels), and kept at -40 ± 2 °C until analyzed for total phosphorus, orthophosphate, nitrates, and nitrites. For analyses of nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and total aerobic bacteria in the sediments, samples were taken close to the plants (from 30 cm to 1 m from the main trunk) and a few centimeters from pneumatophores (aerial roots), using an aluminum soil core sampler (diameter: 1 cm; depth: 5 cm). Samples were kept in plastic bags at 4 ± 1 °C until analyses. Small portions of the top layer of sediment were collected and placed in sterile plastic Petri dishes, stored at 4 ± 1 °C, and later analyzed for total coliforms, fecal coliforms, and microbial photosynthetic pigments.

2.3. Physical and chemical analyses

All environmental parameters were measured in situ in the mangrove seawater using portable field instruments. Salinity was determined with a refractometer (Aquafauna Biomarine, USA); pH by a field

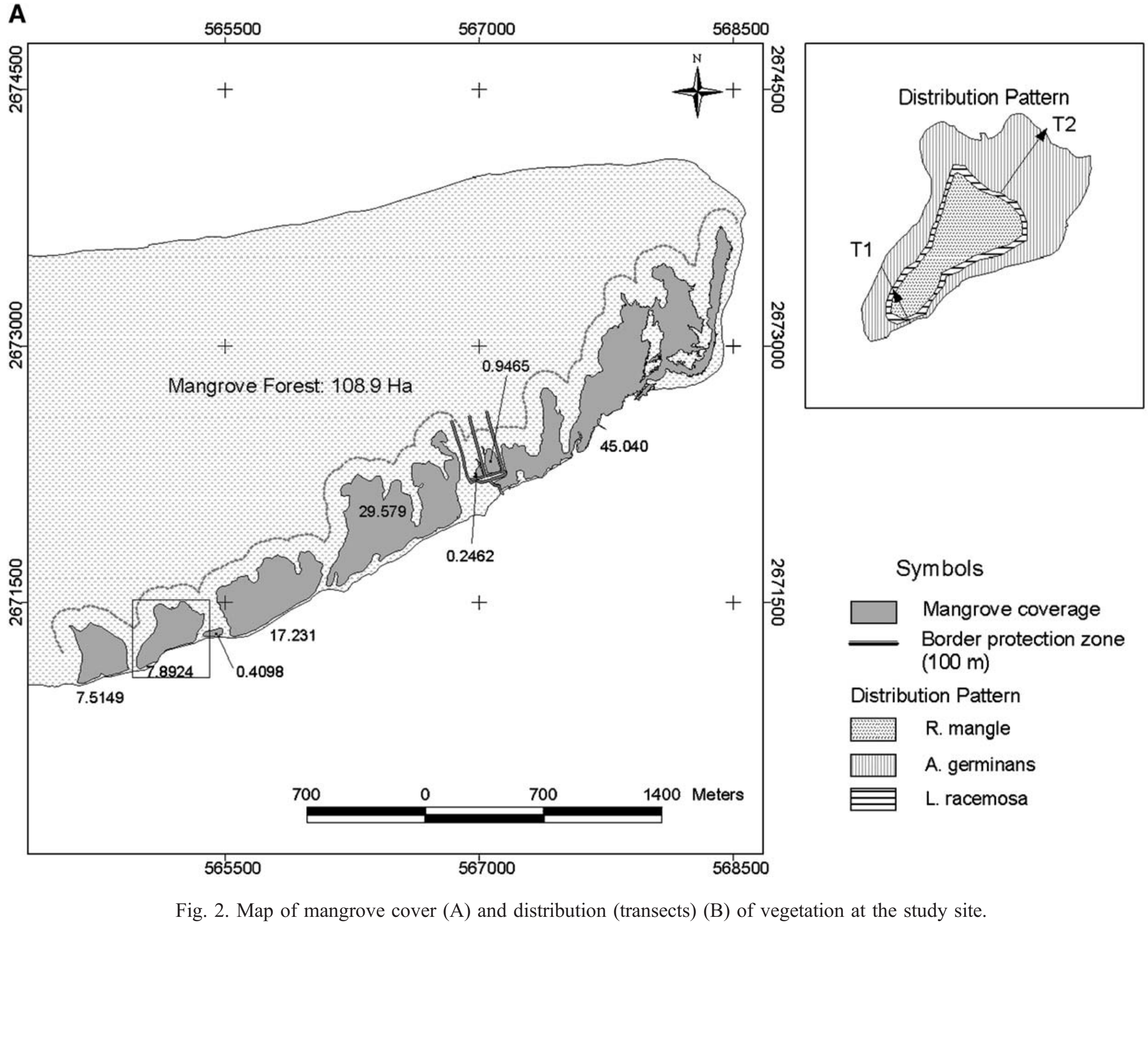

Fig. 2. Map of mangrove cover (A) and distribution (transects) (B) of vegetation at the study site.

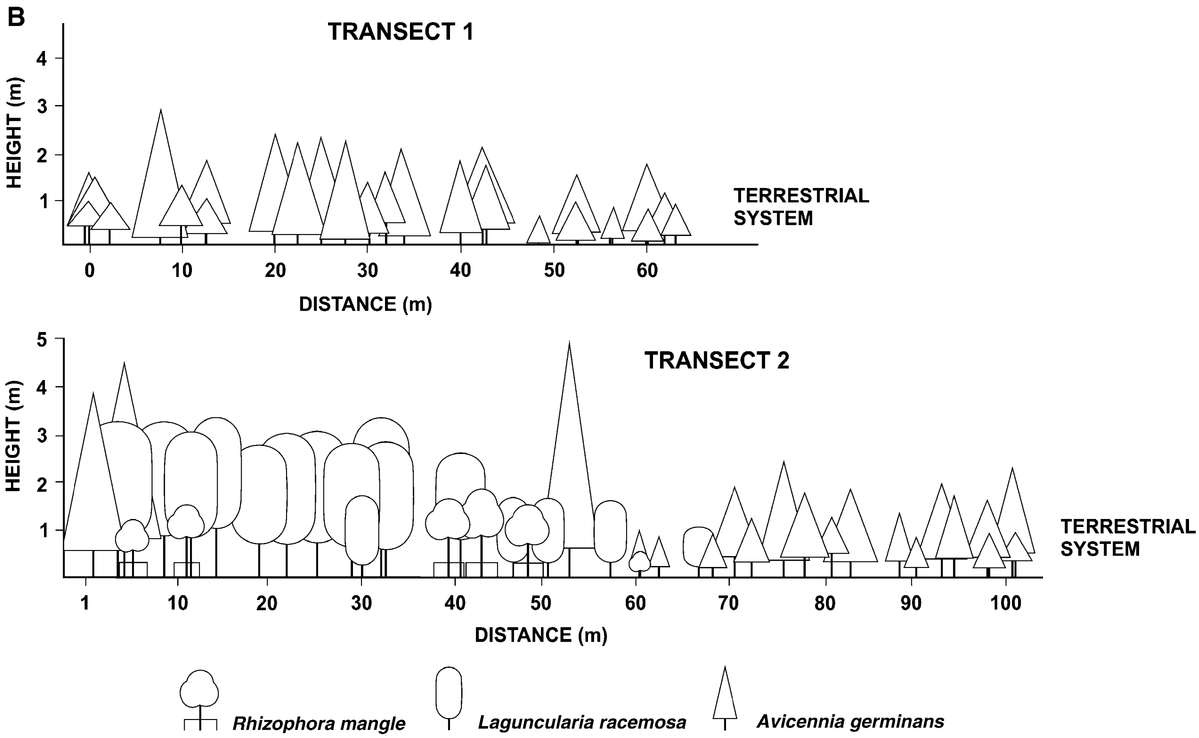

Fig. 2 (*continued*).

pH-meter (B-213, Horiba, Germany); and dissolved oxygen by an oxygen meter (830A equipped with Orion DO 083010 probe, Thermo Electron Corp., USA). Total nitrogen concentration of the sediments was measured by automatic micro-Kjeldahl after digestion (Digestion System 12.1009, and Kjeltec Auto 1030 Analyzer, Tecator, Höganäs, Sweden). Total phosphorus, orthophosphate, ammonium, nitrate, nitrite, and organic matter in seawater were measured by standard methods for water analysis (Strickland and Parsons, 1968).

2.4. Mapping mangroves

The mangrove cover was mapped from recent aerial photos of the site (Proyección Universal Transversal de Mercator, Datum ITRF92, Elipsoide GRS80, code G12D82C and G12D83A, pixel size 2 m, INEGI, Mexico, 1993). A digital-photo interpretation was performed as described by van Zuidam (1986), and the vegetation patches were then identified and digitized at 1:1500, using ArcView version 3.2 software (ESRI, USA). Site verification of the computer analysis was confirmed with a GPS receiver (Garmin III Plus, Garmin International, USA). After confirmation, the area of each mangrove patch and the total mangrove forest area were calculated. Finally, we marked the border of the Protected Zone (SEMARNAT, 2003), using the same ArcView software to confirm location.

During field surveys, we prepared a list of plant species in the study areas using the keys in Mason (1957) and Wiggins (1980). We selected a representative patch of mangrove, based on previous studies of the area (Jimenez, 1991; Gonzalez-Zamorano, 2002), to create two transects 60 and 100 m long for recording detailed structural data (plant species and height). With these data, a map of the vegetation of the study area was prepared (Fig. 2).

2.5. Microbial analyses

Total aerobic culturable bacteria, N_2-fixing bacteria, phosphate-solubilizing bacteria, total coliforms, and fecal coliforms were evaluated using standard microbiological methods. N_2-fixing bacteria were cultivated on marine, N-free HGB medium (Holguin et al., 1992) and counted by the MPN-acetylene reduction assay (MPN-ARA) described by Limmer and Drake (1998). Acetylene reduction of soil cores was assayed by placing them in 70-ml serum bottles wetted with 10 ml filtered sterile seawater. The rest of the ARA procedure was performed as described previously (Holguin et al., 1992). Phosphate-solubilizing bacteria were counted by the plate count method, using SRSM1 medium containing insoluble calcium phosphate (Vazquez et al., 2000). Total aerobic, culturable marine bacteria were enumerated similarly on marine medium no. 2216 (Merck). Coliform were determined by the MPN method on lactose broth (Difco, USA) and confirmed by brilliant green bile 2% (Difco) according to the techniques described by Mexican regulations (SEMARNAT, 1987). Microbial photosynthetic pigments in the top sediment layer (<1 cm depth) were analyzed by an HPLC method developed for phytoplankton (Vidussi et al., 1996).

Phytoplankton were harvested with a phytoplankton net (30 cm diameter, 64-μm mesh) at a depth of 50 cm on the seashore at the entrance to the mangrove feeding channel. Samples (50 ml each, in triplicate) were preserved with 50 ml fixative (water/ethanol/formaldehyde, 6:3:1). Fixed samples were later observed with a light microscope (Zeiss, Germany), counted by phase-contrast microscopy, identified, and photographed (Tomas, 1996).

2.6. Census and analysis of bird occurrence

Birds were counted by using transects (Buckland et al., 1993; Bibby et al., 2000) by the "fixed point method" (Reynolds et al., 1980; Bibby et al., 2000). Birds were observed with binoculars (20 × 50), a telescope (60×), and by listening to their calls. The count was done at 24 stations by two persons for two consecutive days. First, the total number of birds was counted by surveying the fringe of each station. Then we chose, at random, one site for each station and counted birds during a period of 30 min. Later, the data for both methods were combined. The distance between stations was in the range of 114 to 582 m and covered the entire 4.2-km long study area without overlapping territory. Theoretically, each station overlapped the nearby station, but the thick vegetation with the mangroves created independent counting of the birds. The census was repeated several days later for verification. Species was identified according to a checklist (American Ornithologists Union, 1998) and classified as resident or migratory according to Howell and Webb (1995). The birds were further classified on the basis of official status of concern (Norma Oficial Mexicana NOM-059—SEMARNAT, 2002).

2.7. Statistical analysis

Data from four stations were analyzed. Three samples of water and sediment were taken from each station and the entire sampling procedure was

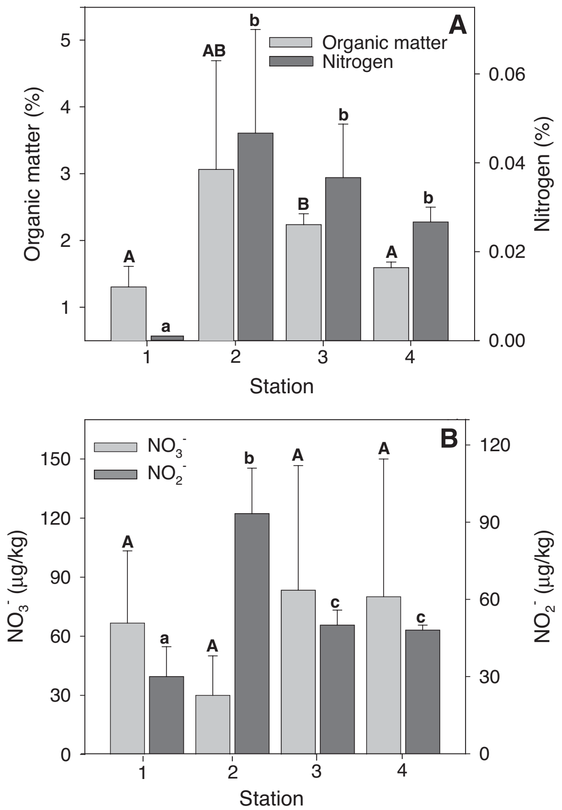

Fig. 3. Total N, NO_3^-, NO_2^-, and organic matter in sediments. Columns for each analysis, denoted by a different letter in subfigures, differ significantly at $P \leq 0.05$ in one-way ANOVA. Bars indicate standard errors.

repeated, 3 weeks later. Every physical and chemical analysis was performed in triplicate for all samples. Data was checked for homogeneity, and therefore, all data were combined and the results, without transformation, were further analyzed by ANOVA, followed by Tukey's post-hoc analysis at $P \leq 0.05$, using a station as one block. To compare each of the four zones used for bird observations, a cluster analysis was done using complete linkages (Sokal and Rohlf, 1979). All analyses used Statistica software (StatSoft Inc., Tulsa, OK). All sampling data are accompanied by standard error (S.E.). Census data (birds and diatoms) appear as total number of individuals of each species.

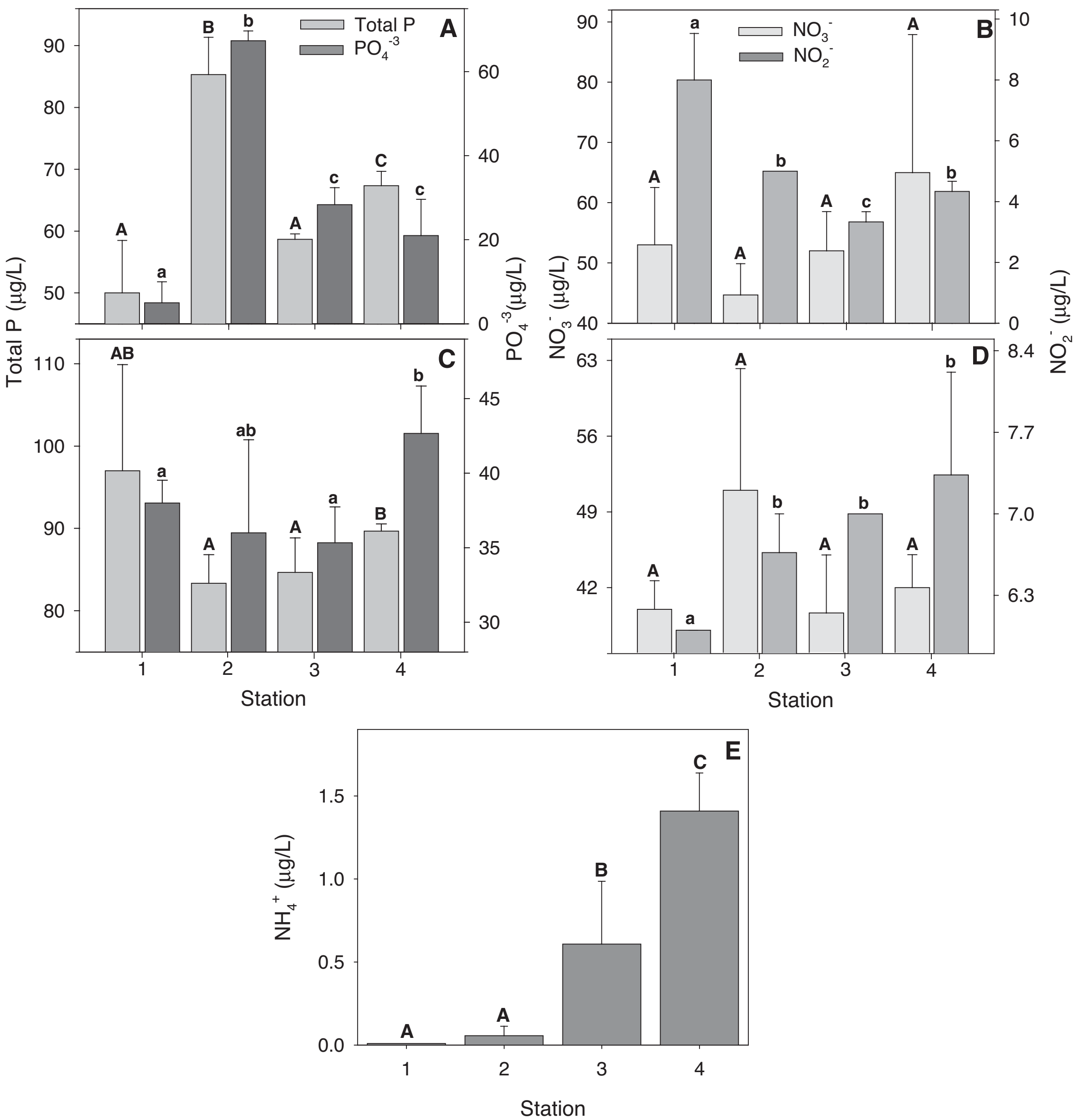

Fig. 4. Total P, NO_3^-, NO_2^-, NH_4^+, and PO_4^{-3} in feeding channel water and in seawater near the mangroves. Columns for each analysis, denoted by a different letter in subfigures, differ significantly at $P \leq 0.05$ in one-way ANOVA. Bars indicate standard errors.

3. Results

3.1. Floral analysis and mapping of the mangroves on El Mogote sandbar

The floral analysis includes three mangrove species (white mangrove, *Laguncularia racemosa* (L.) Gaertn. f., black mangrove, *Avicennia germinans* (L.) L., and red mangrove, *Rhizophora mangle* L.) and five weed species (pioneer herbaceous plants) (*Batis maritima*, L. *Allenrolfea occidentalis* (S. Wats.) Kuntze, *Salicornia bigelovii* Torr., *Salicornia pacifica* Standley, *Salicornia subterminalis* Parish, *Sessuvium portulacastum* L., and *Monantochloe littoralis* Engelm.). The area covered by the eight patches of mangrove (0.25 to 45 ha) was 108.9 ha. Mangrove also occurs along the embankments of an abandoned marina on the sandbar (Fig. 1, the fork-like appearance).

There was a major difference between the area around Station #1 and the other stations. Station #1 is located at the far eastern end of the sandbar in a mangrove that was naturally blocked for 2 years. Without exposure to the regular tides during this period, most trees were dead or suffering osmotic stress caused of salt accumulation (described later). Branches were nearly bare. The entire area was densely covered with the pioneer herbaceous plants (weeds) *S. bigelovii*, *S. pacifica*, and *S. subterminalis*. The feeding channel was re-opened in April 2004, and the lagoons re-flooded (Bashan and Holguin, unpublished data).

This community contained: (i) low canopy trees with an average of 1210 trees ha^{-1}, and (ii) shrubs with an average of 5020 shrubs ha^{-1}. Their height varied according to species (black mangrove < red mangrove < white mangrove). Most were smaller than 3 m, with individuals rising to heights of 7 m. Shrubs were the same species, but under 2 m; shorter individuals grew on the terrestrial periphery of the mangrove swamp, and was almost exclusively black mangrove, many 30–40 cm tall.

Observations of two transects in one patch and general surveys of the other seven mangrove patches showed typical zoning of these species, with black mangroves in the dryer terrestrial areas, red mangroves close to the feeding channels and internal lagoons (where they exist), and white mangroves in between (Fig. 2b).

Proximity to the water controlled the size of individual plants: black mangroves close to water were tall (4–5 m) with a well-developed trunk (>10 cm diameter), while those on the terrestrial border of the site were small (<1 m) and shruby. White mangroves were distributed similarly. Red mangroves close to water were 3 to 5 m tall with thick trunks and those close to the black mangrove zone were smaller (1.5 to 2 m, with trunk diameters <10 cm).

On-site analysis, combined with aerial photography, provided data for a map detailing the distribution of mangroves on El Mogote sandbar (Fig. 2a).

3.2. Determination of total N, NO_3, NO_2, NH_4^+, PO_4^{-3}, organic matter, and pH in the sediment and seawater of the feeding channels

The concentrations of organic matter in the sediment were low at all stations (<4%), as were those of

Table 1
Changes in salinity, pH, and dissolved oxygen at the mouth of feeding channels and salinity within feeding channels at four stations on El Mogote Sandbar

Station	Sampling site	Salinity (psu)	pH	Dissolved oxygen (mg l^{-1})
1	Mouth of feeding channel	34.4 ± 0.2	7.1 ± 0.1	5.7 ± 0.1
	Blocked lagoon[a]	85.1 ± 0.3	ND	ND
2	Mouth of feeding channel	34.6 ± 0.2	7.6 ± 0.1	6.4 ± 0.1
	Within feeding channel	39.7 ± 0.7	ND	ND
3	Mouth of feeding channel	35.5 ± 0.3	7.6 ± 0.1	6.4 ± 0.2
	Within feeding channel	36.5 ± 0.0	ND	ND
4	Mouth of feeding channel	40.1 ± 0.2	7.3 ± 0.1	5.0 ± 0.5
	Within feeding channel	39.8 ± 0.1	ND	ND

ND—not measured.
[a] This site is a lagoon with a blocked feeding channel.

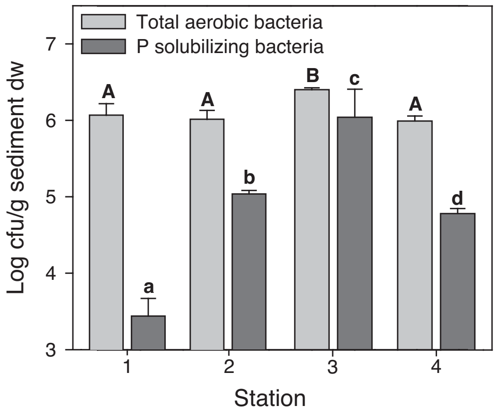

Fig. 5. Total culturable aerobic bacteria and phosphate-solubilizing bacteria (PSB) in mangrove sediments. Columns for each analysis, denoted by a different letter in subfigures, differ significantly at $P \leq 0.05$ in one-way ANOVA. Bars indicate standard errors.

total N, NH_4, NO_3, and NO_2 (Fig. 3). The seawater in the feeding channel at all stations had low concentrations of total P and nitrates and lower concentrations of orthophosphate, while the nitrite concentrations were below the detection level of the equipment (Fig. 4). Similar results were obtained for the seawater in front of the feeding channel entrances. The concentration of total phosphorus within the feeding channels was higher than outside. The concentration of ammonium in the seawater in front of the mangroves was very small, although it varied among stations (Fig. 4). The pH of sediments at all stations was high and similar: Station #1: 7.93 ± 0.04; Station #2: 7.97 ± 0.11; Station #3: 7.57 ± 0.09; Station #4: 7.75 ± 0.38 (mean and standard error).

Table 2
Concentrations of photosynthetic pigments (μg g^{-1}) in mangrove sediments

Pigment	Station #1	Station #2	Station #3	Station #4
Chlorophyll *a*	36.6	21.2	21.1	6.43
Chlorophyll *b*	1.56	0.43	1.05	0.303
Chlorophyll *c*	1.05	3.02	1.44	1.06
Fucoxanthin	2.85	5.59	3.41	1.94
Diadinoxanthin	0.90	1.69	1.28	0.45
Zeaxanthin	2.30	1.09	0.95	0.19

Data are average of two samples performed three weeks apart, except for chlorophyll *b*, which represents a single sample.

3.3. Determination of salinity, pH, and dissolved oxygen in seawater at the entrance of the feeding channels, and salinity within the feeding channels

Salinity within the channels was significantly higher than that at the entrance of the channels connecting with the lagoon. Two unusually high salinity values were detected: At Station #4, at the northwest corner of the lagoon, salinity was higher than at the other stations. Salinity at the blocked lagoon (Station #1) reached extremely high concentrations (200 g l^{-1} water) and salt crystallization on dry surfaces was observed. Although pH varied among the stations, it was within the pH range for lagoon seawater. The

Table 3
Abundance and locations of phytoplankton in mangrove sediment (organisms ml^{-1} seawater)

Species	Station #1	Station #2	Station #3	Station #4
Diatoms				
Achanthes sp.				1
Bacteriastrum truncatum	7	1		1
Bacteriastrum sp.	7	1		
Bacteriastrum delicatum	1			
Cocconeis sp.			1	
Coscinodiscus sp.	1	1		
Cyclotella sp.	1		1	
Cymbella sp.	1		2	1
Chaetoceros aequatorialis	7	4	1	1
Chaetoceros spp.	34	22	53	10
Diploneis sp.		1		1
Epithemia sp.			2	
Gomphonema sp.	1			
Guinardia sp.	1			
Melosira sp.	1			
Navicula spp.	1	1	3	2
Nitzschia sp.	12	6	6	1
Nitzschia longissima	2	1	2	4
Odontella sp.	1	1	1	
Pinnularia sp.			1	1
Pleurosigma sp.	1		1	4
Pseudo-nitzschia sp.	4	7	7	
Rhizosolenia sp.	1	1		
Skeletonema sp.		1		
Stephanopyxis sp.	1			
Synedra sp.				1
Thalassionema sp.	3			
Thalassiosira sp.			1	
Dinoflagelates				
Ceratium sp.	1	1	1	

concentration of dissolved oxygen at Station #4 was significantly lower than at the other stations (Table 1).

3.4. Determination of key microbial populations

Total coliform and fecal coliform in both sediment and water at the four stations were low, and well below the limit set under Mexican law (200 cells in 100 ml of water). At Stations #1–3 total and fecal coliform counts (MPN 100 ml^{-1}) in sediment and water of feeding channels is less than 2, except for Station #4, with higher counts: 4–5 MPN 100 ml^{-1} in the sediment and 23 in the channel water. N_2-fixation (acetylene reduction) in sediment revealed high activity only at Station #3 (198 ± 3 μmol ethylene g^{-1} dw sediment). It was lower at Stations #2 and #4,

Table 4
Abundance and composition of bird species at mangrove study sites

Common local name	Common English name	Scientific name	Occurrence area				Total
			M	B	W	F	
Zambullidor moñudo[a]	Eared grebe	*Podiceps nigricollis*	0	6	0	0	6
Bobi	Blue-footed Boobie	*Sula nebouxii*	1	0	5	0	6
Pelícano	Brown pelican	*Pelecanus occidentalis*	20	190	0	0	210
Pato buzo	Double-crested cormorant	*Phalacrocorax auritus*	3	11	10	0	24
Tijereta	Magnificent frigatebird	*Fregata magnificens*	18	21	0	0	39
Garza gris	Great blue heron	*Ardea herodias*	0	2	3	0	5
Garcita nivea	Snowy egret	*Egretta thula*	3	1	0	0	4
Garza rufa	Reddish egret	*Egretta rufescens*	3	1	0	0	4
Garza tricolor	Tri-colored heron	*Egretta tricolor*	5	0	0	0	5
Pedetre azul	Yellow-crowned night-heron	*Nyctanassa violacea*	6	0	0	0	6
Ibis blanco	White ibis	*Eudocimus albus*	0	1	0	0	1
Zarapico[a]	Willet	*Catoptrophorus semipalmatus*	1	0	0	0	1
Picopando[a]	Whimbrel	*Numenius phaeopus*	3	0	0	0	3
Gaviota enmascarada[a]	Laughing gull	*Larus atricilla*	1	6	0	0	7
Gaviota parda[a]	Heermann's gull	*Larus heermanni*	8	67	15	0	90
Gaviota picoanillado[a]	Ring-billed gull	*Larus delawarensis*	6	4	0	0	10
Gaviota reidora	Yellow-footed gull	*Larus livens*	6	54	65	0	125
Gallito caspio[a]	Caspian tern	*Sterna caspia*	22	9	0	0	31
Gallito máximo[a]	Royal tern	*Sterna maxima*	0	62	0	0	62
Gallito elegante[a]	Elegant tern	*Sterna elegans*	2	0	0	0	2
Gallito marino californiano[a]	California least tern	*Sterna antillarum browni*	1	0	0	0	1
Paloma taravilla	Mourning dove	*Zenaida macroura*	11	0	0	0	11
Dendroica	Yellow warbler	*Dendroica petechia*	40	0	0	0	40
Paloma pitahayera	White-winged dove	*Zenaida asiatica*	42	0	0	0	42
Gavilán rastrero	Northern harrier	*Circus cyaneus*	1	0	0	0	1
Tildillo	Wilson's plover	*Charadrius wilsonia*	0	0	0	7	7
Verdín	Verdin	*Auriparus flaviceps*	15	0	0	0	15
Carpintero	Gila woodpecker	*Melanerpes uropygialis*	1	0	0	0	1
Pajaro azul	Western scrub-jay	*Aphelocoma californica*	5	0	0	0	5
Picopando[a]	Marbled godwit	*Limosa fedoa*	0	0	0	3	3
Gavilán pescador	Osprey	*Pandion haliaetus*	1	0	0	0	1
Alzacolita[a]	Spotted sandpiper	*Actitis macularia*	0	11	1	0	12
Lelo	Ash-throated flycatcher	*Myiarchus cinerascens*	2	0	0	0	2
Chuparrosita	Costa's hummingbird	*Calypte costae*	3	0	0	0	3
Calidris[a]	Sanderling	*Calidris alba*	0	9	0	0	9
Cardenal	Northern cardinal	*Cardinalis cardinalis*	3	0	0	0	3
Aura	Turkey vulture	*Cathartes aura*	1	0	0	0	1
Vermivora[a]	Orange-crowned warbler	*Vermivora celata*	10	0	0	0	10
Total			244	455	99	10	808

Areas where found: M = mangrove; B = beach; W = sea; F = mudflat.
[a] Migrating birds.

(9.55 ± 1.3, and 2.6 ± 1.4 μmol ethylene g^{-1} dw sediment), and nil at Station #1. In the total aerobic culturable bacteria, of which phosphate-solubilizing bacteria were a large fraction (<80%), density was high and similar at all stations, except Station #1, which was lower (Fig. 5). Microbial photosynthetic pigments varied among stations. The lowest concentration of photosynthetic pigments was detected at Station #4, while the highest concentration was detected at Station #2 (Table 2). Twenty-nine species of phytoplankton were detected and counted. Diatoms dominated phytoplankton population at all stations, amounting to a total of 28 species, and only one species of dinoflagelate. Five species of phytoplankton were detected at all four stations, six at three stations, six at two stations, and 12 at only one station (Table 3).

3.5. Determination of bird populations

In the bird census, 38 species were observed, of which 14 were migratory and 24 residents. Most of the birds were seen on the beach (56%), 30% resided inside the mangrove canopy, 12% in the nearby seawater, and only 1% on the mudflats (Table 4). Four species were most common: *Pelecanus occidentalis*, *Larus heermanni*, *Larus livens*, and *Sterna maxima*. These species use the lagoon for feeding and the beaches for resting. Cluster analysis (not shown) revealed that the most relevant zones for the birds were the mangrove areas and the beach (Table 4).

Of the 38 species, 6 (16%) are protected by Mexican law: *Ardea herodias*, *Egretta rufescens*, *Larus heemanni*, *L. livens*, *Sterna antillarum browni* (danger of extinction), and *Sterna elegans*. Three species used the mangroves for breeding: *Auriparus flavipes* (7 nests), *Zenaida asiatica* (5 nests), and *Zenaida macroura* (1 nest). The endangered species *S. antillarum browni* used the slightly higher ground of the mudflats near Station #4 as a primary nesting site.

4. Discussion

Encroachment of urban development on mangroves in Latin American and Asian coastal areas is an inevitable process. Even where mangroves are protected by law, urbanization can reach the limits of protected areas (Zan et al., 2003). Human activities, including residential development (this study), recreation (Toledo et al., 2001), and civil engineering projects, such as roads, ports, airports, landfills, and wastewater treatment plants (Wong et al., 1997) are decimating mangrove coverage. Yet, the possibility of continuous destruction of mangroves from accelerated urbanization has created public concern to conserve this wetlands environment.

Although mangroves have some legal protection in Mexico, basic information, including species composition and physicochemical and biological indicators of health, are required for effective management. Such information is scarce (Flores-Verdugo et al., 1993; Tam et al., 1997) or, in the case of mangroves in arid climatic areas, practically non-existent. Usually, mangroves start showing stress at the end of a slow process of environmental deterioration of the habitat. Therefore, the purpose of this study was first to collect basic information and identify physicochemical and biological indicators of healthy mangroves. This will allow a baseline that will help manage this ecosystem in an intelligent manner, including threshold parameters before urban development reaches them. Hopefully, this will alert managers to stress conditions before mangroves show visible signs of deterioration. Additionally, this general analysis of a healthy mangrove habitat provides tools for assessing environmental impacts on arid zone mangrove communities, which Mexican law still requires, prior to any use of nearby land.

4.1. Geographical and floral indicators

Organisms in the mangroves bordering the lagoon, Ensenada de La Paz, are more abundant but less diverse, compared to other tropical mangroves (Tomlinson, 1994). Mangrove are shorter (<5 m), in general, than in the tropics (Primavera et al., 2004) and are mostly shrubby. This is a consequence of rare fresh water run-off and seasonal hurricanes (Flores-Verdugo et al., 1993). The habitat consists of discrete patches separated by sand dunes, a distribution more similar to patches of mangrove remaining in Hong Kong (Tam et al., 1997) than extensive tropical mangroves typical of southern Mexico (Flores-Verdugo et al., 1990). Its composition consists of three mangrove species and several coastal shrubs and pioneer plants, as elsewhere in the Gulf of California (Arreola-Lizárraga et al., 2004; Flores-Verdugo et al., 1993; Toledo et al., 2001).

4.2. Physicochemical indicators

The physicochemical indicators in seawater and sediment (salinity, dissolved oxygen, and pH) were similar to those of another intact arid climate mangrove, the Balandra mangrove and cove (Giani et al., 1996), with the exception of the extreme salinity in the mangrove with the blocked channel at Station #1 and the relatively high salinity at Station #4. Possibly, circulation of water is poor, and high air temperature and daily winds enhance evaporation, leading to higher salinity at Station #4. Nevertheless, no measurable effect of higher salinity on any biological indicator was observed in comparison to other stations.

Nitrogen fixation is a major bacterial activity in mangrove ecosystems, second only to carbon decomposition by sulfate-reducing bacteria. These bacteria might supply 40–60% of the nitrogen requirements of the ecosystem (Toledo et al., 1995; Holguin et al., 2001). Acetylene reduction assay (ARA) performed on core samples of sediment showed that nitrogen fixation was taking place at three stations. Station #4 had low N_2-fixing activity, perhaps because of relatively high ammonium content in the seawater, which is sufficient to block nitrogenase activity (Klassen et al., 1997). No nitrogen-fixing activity was detected at Station #1, probably a consequence of extremely high salinity in the sediment, the cause of death for many trees. Stations #2 and #3 showed the highest N_2-fixing activity; the sites surrounding these stations also appeared healthier. Some reports suggest a correlation between nitrogen pollution and low nitrogen fixation in mangrove communities (see review, Holguin et al., 2001). These results suggest that N_2-fixation in sediments, measured as ARA, can be used as an indicator of the health of a mangrove in an arid climate environment.

4.3. Biotic indicators

Phosphate-solubilizing bacteria (PSB) at all stations except Station #1 were high relative to the total culturable aerobic bacteria. These results suggest that the ratio of PSB to total aerobic bacteria can be used as an indicator of mangrove health. Previous work suggested that PSB supplies available phosphate to the plants (Vazquez et al., 2000; Holguin et al., 2001; Rojas et al., 2001), promoting development and growth of a mangrove community. The concentration of orthophosphate (the soluble form of phosphate available to plants) in sediments was very low at all stations.

The negligible amounts of coliform and fecal coliform and the low organic matter detected suggest that the nearby city and its wastewater treatment plant supply only marginal contamination.

Analysis of phytoplankton communities revealed that the dominant phytoplankton in the mangroves were diatoms. Few diatom genera observed in this study were detected before in the Balandra cove 25 km north of El Mogote (Siqueiros Beltrones and Sánchez Castrejon, 1999), but most were different from those in the former study. This difference could be that the season of sampling or the salinity of the two lagoons may be different (Siqueiros Beltrones and Sánchez Castrejon, 1999). The presence of diatoms, such as *Chaetoceros* spp., *Thalassiosira* spp., and *Biddulphia* spp. (all species found in this study), is related to good quality water (Devi and Lakshminaryana, 1989). The dominance of *Chaetoceros* spp. in the phytoplankton community is common in warm waters (Jacob et al., 1982). That there were abundant diatom species at Stations #2–4, and that the diversity of most aquatic systems decreases with eutrophication, is an indication that these mangroves are in good health (Prepas and Charette, 2003).

Photosynthetic pigments are used to characterize water bodies. Fucoxanthin is an indicator for diatoms, zeaxanthin for cyanobacteria, chlorophyll *b* for Chlorophyceae, and chlorophyll *a* for cyanobacteria. Chlorophyll *a* also indicates a value for all other algal groups and is, therefore, used to calculate algal biomass (Ston and Kosakowska, 2000). Chlorophyll *c* and diadinoxanthin are present in many algal groups. Analysis of photosynthetic pigments in the sediments of Station #1 showed extremely high concentrations of chlorophyll *a*, reported as indicative of a hypertrophic system (Prepas and Charette, 2003). However, analysis of nitrogen and phosphorus revealed very low concentrations of nutrients in the sediments. Since the main pigments found in the sediments of Station #1 were zeaxanthin and chlorophyll *a*, this indirectly indicates an abundance of cyanobacteria. Most probably the extremely high salinity of the sediments at Station #1 impeded growth of other microalgae, resulting in a cyanobacterium bloom. The sediment from Station #4 had the lowest concentrations of all photosynthetic pigments. This is a consequence of the especially sensitive nature of diatoms to changes in salinity, pH, and concentration of organic matter (Guillard and Kilham, 1977). Salinity and ammonium concentrations at Station #4 were higher than at Stations #2 and #3. Our results suggest that cyanobacterial blooms and the halophyte of the genus *Salicornia* that proliferates in the area, besides being used as indicators of eutrophication in some aquatic habitats, can also be used as an indicator of a degenerated mangrove habitat, since the trees were dying around Station #1.

Mangroves are important for resident and migratory birds (Whitmore et al., in press), serving as feeding, protection, breeding, and nesting areas. They also serve as resting areas for birds waiting for the tide to recede to allow easier feeding. As expected from ecological theories, we found many more birds in the mangrove and the beach than in the water or on mud flats. This suggests that the birds find the mangrove suitable and safe. The occurrence of birds in a mangrove could be used as an indicator of mangrove ecosystem health.

The bird tally was over 800 birds nesting, resting, or feeding in the mangroves, belonging to only 38 species, of which one is protected as endangered, and eight others have special protection under the Mexican protection law. One species, California least tern *S. antillarum browni*, is included in the US list of threatened species. However, none of the other species are included in this list. Although not listed as threatened, all migratory species are protected by USA law under the migratory bird act (Bean and Rowland, 1997).

4.4. General conclusions

Baseline data gathered in this study may help manage these protected mangroves when urban areas reach their perimeter (only a 100-m buffer zone is needed by Mexican law). Future surveys of the parameters measured in this study will offer data to estimate ecological pressure on the mangroves. This will give authorities a tool to manage and preserve these arid mangroves.

In summary, this comprehensive study shows no indication of contamination in any of the mangrove patches studied on El Mogote, despite their close proximity to an urban area. The poor state of one of the mangrove communities, indicated by sparse tree coverage and many dead trees, showed no nitrogen-fixing activity, few phosphate-solubilizing bacteria, a high concentration of cyanobacterial pigments in the sediment, and no diatoms. Two of the four mangrove communities were in relatively pristine condition, as indicated by phytoplankton and microbial communities in the water and sediments. Our data suggest that microbial analysis and the common occurrence of birds in a mangrove community are useful indicators of system health, and provide a baseline for future management of these and other mangroves in zones of arid climate.

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