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Transitional Mangrove Scrub North of La Paz and Magdalena Bay in Baja California, Mexico: A Historical Review

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ABSTRACT

The location and topography of the 1,300 km Baja California peninsula west of the Sonoran Desert provide the most extreme conditions for mangrove forest growth in the Northern Hemisphere. Despite their small size, however, the dwarf shrub mangroves (<2 to 4 m) are important for global CO_2 sequestration, and monitoring of their expansion or decline is needed as part of assessing global carbon fluxes and biodiversity. Mangrove distributions at 42 coastal sites in 1972/73 are compared to historical accounts and modern data. These data show that there has been almost no northward migration of *Rhizophora mangle* during the past century although *Avicennia germinans* and *Laguncularia racemosa* have spread north on the Gulf Coast. The dwarf mangrove plant biodiversity in 1972/73 is related to geoform, temperature (T) and seasonal precipitation (P), but mangrove species cluster by annual P and T. The present northernmost Baja California mangrove limits are at 26.79° N on the Pacific Coast, and at 29.04° N on the Gulf Coast mainland, close to limits recorded in 1921. However, there are notable (46 to 4,649 ha) increases in areal cover and canopy height at these northern sites, and in other areas remote from urbanization. Case histories for seven locations point to increasing frequency and severity of tropical storms as main drivers of change on both coasts. However, anthropogenic changes from tourism promotion are major hazards to survival of the Gulf Coast forests, despite international, governmental and public efforts to legislate nature preserves. On the Pacific Coast, rising seawater temperatures may create coastal current conditions that potentially allow the extension of red and white mangrove ranges into northwestern Baja California. However, hazards associated with ocean warming that promotes tropical storm frequency and intensity can have predominantly negative impacts on mangrove production. These extreme hazards counteract the benefits of local and regional protection and management efforts.

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Introduction

"We suppose it is the combination of foul odour and the impenetrable quality of the mangrove roots which gives one a feeling of dislike for these salt-water-eating bushes." (Steinbeck, 1951).

Despite the scathing words written about mangroves in Baja California by Steinbeck in 1951, the importance of mangrove forests and their large scale loss on a global scale are now well-known and of great concern [1-3]. These studies document the harmful impacts of large-scale tropical mangrove forest removal as a result of harbour development, firewood collection, salt harvesting, aquaculture, and agriculture. In the Gulf of Mexico alone, a 20% loss of an original 6,600 km^2 area of mangroves was reported for the decade 1983 − 1992 [1]. Also, despite protecting laws, there was a further loss of c. 700 km^2 in Mexico from 1993 to 2000 [4]. Much less is known, however, about the value and vulnerability of low-growing mangrove scrub forests in the transitional zone between the tropics where there are diverse mangrove trees and temperate regions where frost prohibits mangrove survival. A total of 33,446 ha of estuarine wetlands with mangroves was reported by Gonzáles-Zamorano et al (2012). for the Baja California Peninsula, of which 0.1% to 96.2% included mangrove cover. Whitmore et al considered the Baja California Sur mangroves to be an endangered ecosystem, based on a 1994 estimate of only 12,120 ha of "manglares" (2.5% of the total of 488,367 ha for all Mexico).

Because of the low stature (<2 m) of the transitional dwarf/scrub mangroves (Figure 1), there has been a tendency to regard this coastal vegetation type as ecologically insignificant and of low concern for future protection. However, it is now known that semi-arid "dryland forests" play an important role in CO_2 sequestration and Earth's albedo-regulated heat balance, thereby moderating global warming trends [5]. Furthermore, recent studies show that large amounts of carbon are sequestered as peat within the dwarf mangrove forests of Baja California [6]. Although the leaf-litter production of the Pacific scrub mangroves in northern Sonora is the lowest ever measured, mangrove litter production is up to 9-times greater in southern Baja California scrub, making it comparable to tropical mangrove forest production [7-10]. Hence, despite its insignificant appearance, mangrove scrub plays an important role in carbon cycling in addition to its roles in shoreline

stabilization, wetland biodiversity, fish nurseries, and as gene-pools for development of salt-resistant agricultural crops [11-13].

Also, the socioeconomic studies of López-Medellín et al. show that traditionally, the NW Pacific scrub mangroves are important sources of wood, tannin, medicine; in Sonora, they are also used for religious practices.

Figure: 1 Baja California dwarf mangrove scrub at Laguna de Abreojos, its northern Pacific Coast limit. Left: *Laguncularia racemosa* fringing channels (1972 archive photo). Right: *Rhizophora mangle* and *Spartina foliosa* in low marsh, 2014 (courtesy of I.C. Feller, Smithsonian Inst.).

In this paper, we investigate some historical changes in the mangrove scrub vegetation of Baja California (Figure: 2) that was little studied before 1973 when the population of this Mexican state was less than 250,000. Baja California (c. 1300 km-long) is the second-longest peninsula in the world but until recently, it was sparsely populated (c. 95,000), and its 3,000 km-long coastline was mostly inaccessible by road and uninhabited [14]. Our studies cover the time of rapid population growth from 1960, particularly after 1973 when construction of the Trans Peninsular Highway increased tourism up to 29 million visitors by 1991 [15]. By 2015, there were 712,000 permanent inhabitants, and year-round tourist influxes formed the basis of a major industry, raising the total population to 3.15 million by 2010. In particular, we examine the status of the transitional mangrove scrub north of La Paz and central Bahía Magdalena on the east and west coasts of the Baja California Peninsula which is long noted for its high proportion of endemic plant species [16-18]. There are no endemic mangroves on the Peninsula. In 1972, however, our study was the first to record the IUCN red-listed tropical species *Conocarpus erecta* on the Pacific Coast as far as Puerto Chale, 24.424 °N, in addition to the widespread species *Rhizophora mangle*, *Laguncularia racemosa*, *Avicennia germinans*, and *Maytenus phyllanthoides*.

Figure: 2 Map of Baja California Peninsula collection sites 1971 – 1973, climate zones I to VI, and distributions of the main mangroves (see colour-code). Sea of Cortez is between the peninsula and the Mexican mainland (Sonora). T1= boundary between Magdalena Desert and Cape Thorn-forest; T2 = boundary of Colorado Valley and Central Gulf Coast deserts. CFA = California.

The main purpose of this paper is to review the historical botanical reports on the mangroves of Baja California and to provide baseline plant biodiversity data obtained during field work from 1972−1973 at 42 localities (Table 1) for the whole coastal region of Baja California (Figure 2). We also provide case-histories for seven tidal wetlands to allow comparison of recent changes on the Pacific Coast with those on the Gulf Coast northward of the Cape Region where there has been severe loss of mangrove forest because of urbanization and tourism [19-21].

Finally, we evaluate the main stresses and drivers of changes in mangrove extent and growth, and discuss the Baja California mangrove distributions in the context of temperature- precipitation changes over the past century. The new data relate to forecasting future scrub mangrove vegetation expansion or contraction associated with global warming trends in the tropical Pacific and Gulf of Mexico, including changing El Niño patterns [22-25].

Table 1: Locations of 1971-1973 Field Survey Sites with Mangroves

Region/Location	Map position	Collection	GIS Co-ordinates			
Mediterranean Transition	Latitude N		Latitude N	Longitude W		
Tiajuana	32.50	338	32.519	117.049		
Punta Banda	32.00	327	31.734	116.629		
San Quintin	30.533	317	30.434	115.965		
Laguna Manuela	28.25	295	29.251	114.069		
Guerro Negro	28.00	285	27.971	114.066		
Viscaino Area						
La Bocana	26.75	274	26.741	113.635		
El Coyote	26.78	274	26.816	113.482		
San Ignacio	26.67	274	26.762	113.251		
Magdalena Area						
San Juanico	26.33	273	26.316	112.431		
San Gregorio (La Bocana)	26.00	273	26.061	112.276		
San Jorge (La Poza Grande)	24.75	263	25.745	112.010		
Puerto San Carlos	24.67	253	24.792	112.104		
Puerto Balandro	24.50	251	24.811	112.117		
Puerto Chale	24.33	252	24.424	111.544		
Cape Area						
Todos Santos	23.45		23.447	110.234		
Cabo San Lucas			22.891	109.917		
San Jose del Cabo			23.066	109.697		
La Ribera (Los Cabos)			23.630	109.570		
Puerto Balandra		251	24.322697	110.321617		
Pichilingue			24.273883	110.32196		
La Paz	24.17	251	24.126	110.421		
El Mogote			24.173693	110.43663		
Central Gulf Coast						
Punta la Aquililla			25.672	111.205		
Nopolo	25.67		25.919	111.346		
Loreto			26.003422	111.338389		
Sta. Rosalillita			26.500			
Playa el Requesón			26.638	111.832		
Playa Escondida			26.638	111.836		
Bahia Coyote	26.67		26.723	111.912		
Playa el Burro			26.731	111.908		
Playa Cocos			26.744	111.9		
Playa Santispac			26.764	111.892		
Muleje	26.83	273	26.903	111.957		
Sta Rosalia	26.50	272	27.222769	112.21427		
San Lucas	27.17	283	27.227	112.213		
Bahia de los Angeles La Mona	28.83	294	28.952	113.561	28.8833	-113.5
La Gringa			29.901	113.528		
Bahia de los Angeles Ensenada	29.14		29.042	113.543		
Isla Smith			29.078	113.519		
Gonzaga Bay (Ensenada)	29.83	305	29.833	114.444		
El Huerfanito			30.116	114.623		
Isla Angel de la Guarda			29.369	113.434		

Environmental Background

Baja California is a narrow peninsular stretching 1300 km south from the USA/Mexican border (32.5° N, 117° W) to Cabo San Lucas (23.0° N, 110° W). The maximum width is 240 km in the central Viscaino Peninsula area, narrowing southwards to a minimum of 30 km in the Magdalena Plain area [16,26]. In 1974, the peninsula was divided into two Mexican states: Baja California (= BC) from the USA border to 28° N, and Baja California Sur (= BCS) extending south to the peninsular tip just below the Tropic of Cancer.

Geographically, the BC Peninsula is located within the great desert regions of the world, all of which lie between the tropical and temperate zones from 20 – 35 °N [22]. As a western extension of the Sonoran Desert Region (Wiggins, 1980), the climate of the Peninsula is dominated by hot summers and calm dry air within which rainfall seldom occurs.

The narrowness of the long peninsula with a 30,000 km coastline further contributes to its aridity because cold Pacific Currents (13 – 19°C) sweep southwards off the west coast, creating fog and cool breezes onshore. Where the current moves offshore, there is an upwelling of cold water along the coast, especially in the central Vizcaíno Desert region around Punta Abreojos [14]. The upwelling results in a semi-warm marine regime (18 – 22°C) in the Vizcaíno region. The Pacific coast is characterized by high-energy waves and tidal amplitude 2.0–2.6 m, and the climate ranges from temperate (12 – 18.8°C) in the north to semi-warm (18 – 22°C) south of the Vizcaíno Peninsula. To the north, in Zones I and II of Johnson (1977, see Fig. 2), rain (c. 50 – 100 mm^{-a}) is mainly in winter [27].

Southwards from Punta Abreojos, there is a gradation in climate Zone III to a warmer marine regime (22–26 °C) with summer precipitation (160 mm average) which corresponds to the Magdalena sub-region of the Sonora Desert. In both the central and southern sub-regions, precipitation is extremely variable, ranging from 46 to 608 mm annually. The Cape Region, from south of Punta Conejo on the Pacific Coast and La Paz Bay on the Gulf Coast, is in climate Zone IV, the Arid Tropical sub-region of Wiggins [16]. Zone IV is marked by warmer and wetter conditions, mainly due a brief but large spike in summer rainfall. The Zone III/IV boundary at c. 24° N corresponds to the oceanic boundary between tropical and transitional subtropical marine faunas at c. 24° N, where summer SST is 26°C [28,29]. This boundary also separates regions the northern regions with less than 100 mm annual precipitation from the better- watered southern Cape Region.

The Gulf Coast lies in the rain shadow of the eastern peninsular mountain ranges, mainly the Sierra de la Giganta, and it is the driest area. Here temperatures are higher because tropical Pacific Water dominates in the Gulf of California (= Sea of Cortez). The water along the Gulf Coast in Zones V and VI has a mean annual sea surface temperature (SST) of 24°C (c. 16 – 30°C) winter to summer; and evaporation is high, resulting in higher average sea surface salinity (SSS) of 35 – >35.8‰ compared to 33.9 – 34.5‰ in the Pacific Current [28,30].

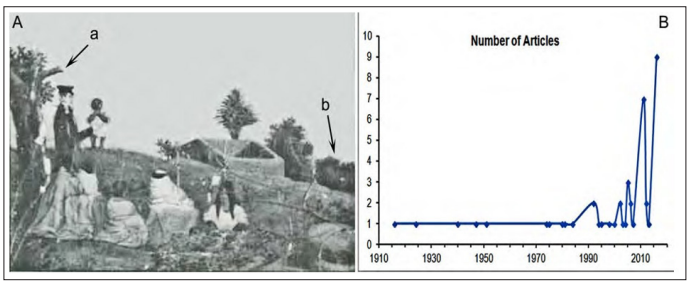
The Gulf also has a much wider annual SST range compared to the West Coast; this range is c. 10°C in the south, increasing to 20°C in the north. Tides are also higher in the northern Gulf (maximum c. 3.4 m) than the Pacific Coast, but spring tides decrease southwards, to 1.8 m in La Paz. Wave energy is also lower along the Gulf Coast, with SST 14 – 30.8°C, and predominantly southerly long-shore currents [27]. The range of precipitation is about the same for the Gulf and Pacific coast of Baja California but the seasonal distribution differs zonally [22]. Winter cyclonic storms from Alaska bring rain to the drier north (climate Zone VI) where rainfall is <100 mm^{-a}, and there may be frost in winter. To the south, there are summer monsoonal ("sonora") storms from the Gulf of Mexico in the Central Gulf Desert climate Zone V. Tropical oceanic storms called *chubuscos* (mild-moderate in strength) and large hurricanes (with gale-force winds) are not uncommon, being linked to El Niño events which are notoriously variable in their occurrence [9]. Zone V broadly corresponds to a Gulf Coast marine region containing colder water animals trapped there during a Pleistocene glacial interval time [31] Escondido is the southernmost site of this cooler water region that is sustained by upwelling and mixing of cold bottom water.

History of Mangrove Surveys in Baja California

The isolated location of Baja California and its sparse population before 1974 means there was little specific information about its desert mangrove scrub forest before our pioneer surveys in 1972 – 73 (Figure 3). Wiggins (1980, p. 40-45) summarized the earliest Baja California botanical explorations, from c. 1751 to c. 1931, but most surveys did not cover the coastal region and few reported on the mangroves. Mangroves are also not mentioned in the earliest plant records made by the Jesuit missionary Johann Jakob Baegert in 1771 and 1772 [32]. Ivan Johnston provides a history of the botanical expeditions to the Peninsula from 1847 to 1916, including locations known to have mangroves today [33]. Johnston's first record is a small collection made around La Paz in 1847 by Major William Rich, a scientific officer in the Mexican- American war (Figure 3A). It is not certain if this collection includes mangroves and also, Major Rich's identifications were not always reliable [34]. In 1887, Edward Palmer collected at Bahía de los Ángeles and Mulejé, and at Guaymas in Sonora but notably, his collection includes only red mangrove from Guaymas which at that time was considered "… *probably the northern limit on the Pacific coast of the tropical or subtropical genera Rhizophora*" [35].

Edward Goldman provides the next Baja botanical history and he mentions the presence of common *Conocarpus erecta, Maytenus phyllanthoides* and *Rhizophora mangle* in the Cape Region [36]. He noted that in 1889 – 1891, the northern Pacific Coast limit of *R. mangle* was reported as San Jorge (c. 25.74° N, -112.010° W).

Figure: 3 History of collections and publications of the Baja Californian flora. A) 1840's poorly preserved, small painting (reproduced from Eyde) that is thought to depict the botanist Major William Rich at La Paz in 1847 near the shore, with heavily cut large trees (a), and shrubby mangroves on a mudflat (b); vertical streaks are cracks in the paint. B) Number of publications per year written about Baja Californian mangroves after the first two reports in the late 1800's [34].



The oldest detailed record of mangroves is from Johnston who collected at 14 Gulf Coast localities in Baja California during

1921 [33]. He describes halophytic communities along the shore, including red, white and black mangroves together with some saltmarsh species, at seven sites from Las Animas to La Paz. He considered that a single "puny" bush of *R. mangle* at Las Animas (about 28.833° N) "…*probably represents the northernmost station on the Pacific Coast*". He reported that the northern limit of mangroves in Sonora, Mexico, seemed to be at Bahía de Tepoca at c. 30° N. This location is close to Puerto Lobos at 30.27° N which is near the northern Sonoran limit reported in 1992 for *Avicennia* [37].

Johnston placed the northern Sonoran limit of *Laguncularia racemosa* at San Carlos Bay near Guaymas 28º N. He reported the northernmost BC location of the species at Mulejé, c. 26.89º N.

The Ricketts-Steinbeck scientific expedition in 1940 was probably the next to collect Baja mangroves — specifically in Cabo San Lucas, La Paz, San Jose Island and Puerto Escondido near Loreto, and possibly at Bahía San Lucas (27.227° N, -112.213° W) [31]. There is no mention of any mangroves further north on the Gulf Coast and larger islands. However, this may reflect the strong bias of the writer John Steinbeck who wrote about the El Mogoté mangroves near La Paz on Easter Friday, 1940:

"*the sharp sweet smell of their flowers, combined with the filthy odor of the mud about their roots, was sickening ….. The roots gave off clicking sounds, and the odor was disgusting. We felt that we were watching something horrible. No one likes mangroves. Raúl said that in La Paz no one loved them at all*".

The next early BC collections seem to be those of Annetta Carter who collected >5,000 Baja plants from 1948 to 1991 [38]. Most of her coastal collection was along the Pacific shoreline from Estero La Bocana to La Ribera. Her vouchers show the presence of *Rhizophora mangle* (*Rm*, red mangrove) and *Laguncularia racemosa* (*Lr*, white mangrove) from Estero La Bocana to Laguna Marina south of Bahía Magdalena, with *Avicennia germinans* (*Ag*, black mangrove) also occurring from Laguna Sta. Domingo to Laguna Marina. Further south, she collected only *Conocarpus erecta* (*Ce*, buttonwood/mangle). On the Gulf Coast, her northernmost mangrove collection site was at Boca el Mojón (27.02 ºN, -112.01 ºW) between San Lucas and Mulejé where she found *A. germinans*. Elsewhere on this coast, she collected *Ag* together with *Rm*, with or without *Lr*, at scattered localities from Bahía Concepción to La Paz.

Shreve and Wiggins reported *Rm* from San Jorge, and at Mulejé, as well as small colonies on Smith Island in Bahía de los Ángeles [26]. They found *Lr* together with *Rm* and *Ag* from Bahía Magdalena (Pacific coast) and Bahía de la Concepción (Gulf Coast) southwards, noting it has hard but brittle wood; *Ag* was also reported from Mulejé. They also found the two mangrove associates: *Ce* on the Gulf Islands and east coast of southern BCS; and *Maytenus phyllanthoides* (*Mp*, mangle dulce/sweet mangrove). The distribution of *Mp* extended from Bahía Magdalena and Isla de la Guarda (north of Bahía de los Angeles) southwards to the Cape region.

Macdonald and Barbour used preliminary data from our 1972 – 1974 collections in thumb-nail vignettes of Baja mangrove distributions [39]. Felger and Lowe studied the coastal vegetation in the northern Gulf of California and reported on Seagrass Meadows with *Zostera* in Bahía Concepción and *Ruppia* at La Paz [40]. They described Mangrove Scrub with *Ag* and *Rm* northwards to Bahía Las Animas, southern Bahía de los Animas, and Isla Smith (at 29.083º N), together with Salt Scrub, including salt grasses, halophytic shrubs and succulent forbs; however, most of this work concerns only island floras. Roberts also summarized the unpublished data collected by the author (PJM) in a research program funded by the Foundation for Ocean Research [41-43]. In 1979, a new survey was made of intertidal halophytes in Baja California, at six Gulf Coast sites from Bahía Gonzaga to La Paz, and at two sites in Magdalena Bay on the Pacific Coast [44]. Notably, Yensen et al. placed the 1979 mangrove limit at Sta. Rosalia for *Rm*, *Lr* and *Ag*. Wiggins also independently reported on the distributions of the four mangrove species and two mangrove associates based on collections between c. 1931 and 1971. He reported essentially the same distribution ranges as in his earlier work, and incorrectly placed the northern limits of scrub mangrove in Magdalena Bay and at Mulejé [16].

Chapman mentioned three mangrove autecological associations (*Rhizophoretum manglae, Avicennietum germinansae, Conocarpetum erectae*) for Baja California but he gave no details and notably failed to report a *Laguncularion* despite the widespread occurrence of *Lr* in the region [45]. A decade later, Peinado et al [46]. described two mangrove associations: *Laguncullariae racemosae-Rhizophoretum mangle* and *Laguncullariae racemosae-Avicennietum germinans* for four Pacific Coast and six Gulf Coast sites (Nopoló to B. de los Angles) in his Tropical Baja Californian region. In 1994, Ramirez-Garcia and Lot also reported on a new field survey made from 1986 to 1988 from Cabo San Lucas and northeastward along the Gulf Coast, and they placed the northern mangrove limit as marked by *Rm* in Bahía de los Ángeles [47].

Whitmore et al. summarize many of these earlier reports [48]. After Mexico contracted with the International Ramsar Convention of Wetlands in 1986, most work was focused on efforts to measure the extent of mangroves using aerial and satellite imagery, and a flurry of papers accompanied this action. Much of this work is in data reports and dissertations not published in the open literature, but the main themes are covered by the work of González-Zamorano et al. [27, 49-51]. There are also other important Spanish papers in three books devoted to the arid mangrove forest (*los manglares*) of Baja California [52-54]. Figure 3B shows the major increase in botanical literature related to Baja California mangroves after 1985, up to 2020.

1972 – 1974 Field Work

Field Methods

Between April 1972 and November 1973, four surveys were made of the Baja California coastal wetlands and beach vegetation at 42 localities, over a period of 12 weeks during spring and fall. The survey sites were reached by Land-Rover jeep and a Volkswagen Bug car equipped with inflated dune-buggy tires. Navigation was by compass, road directions and maps in Gerhard and Gulick's guidebook which was the most detailed and reliable source available before the opening of the Transpeninsula Highway in 1974 [55]. At each site, floristic and baseline qualitative ecological characteristics of the vegetation were recorded to provide a preliminary analysis of the phytogeography and floristic diversity of the arid-region vegetation as related to the climate, soil salinity, and coastal morphology. Surveys 1 km or longer were made by three collectors, who searched lines parallel and at right angles to the shore, recording record all Angiosperm plants present. In addition, at Bahía Magdalena and La Paz, a zodiac rubber boat was used to extend these surveys to the major mangrove areas visible from the road or described by local fishermen. A total of 333 mangrove and saltmarsh voucher plant specimens were collected, including 18 from northern Sonora in 1969. The vouchers are deposited at the San Diego Museum of Natural History where the herbarium curators Reid Moran and subsequently Jon Rebman validated and/

or updated the taxonomy. Methods, voucher location, and results of the beach vegetation studies are reported elsewhere [56].

At six of the 25 sites with mangroves, 1 m-wide transects were made from mean lower water (MLW) to the storm tide line. Elevation was measured by height above the MLW reference point determined from tide tables, and all plant species were recorded on one or more transects. At 10 m intervals, species were assigned to one of six cover classes: <1%, 1-10%, 10-25%, 25-50%, 50-75% and 75-100%. In each marsh zone, salinity of the surface water or soil water in a shallow test-hole was measured using a Goldberg salinity refractometer. This type of refractometer is specifically calibrated to the normal seawater standard of 35‰ (parts per mille), which is essentially the same as the currently used dimensionless value of 35 in psu (practical salinity units).

Results and Data Analysis

The distributions of mangroves and associated saltmarsh plants at the 42 sites in 1972 – 1974 are shown in Table 2. Details of the herbarium collection are given in the Appendix, including ecological notes. Additional details of the transect studies are shown in Section 5, as part of the Selected Case Histories.

Pacific Sites in 1972 and 1973

Climate Zones I and II

Field work in 1972 focused on the Pacific Coast, ranging from the tidal barrier lagoon Laguna Manuela in the Mediterranean-Viscaino Desert transition Zone II (Figure: 2) south to San Jose del Cabo in the tropical thorn forest Zone IV. The tidal wetland in at Laguna Manuela had a high marsh dominated by *Distichlis littoralis*, with *Frankenia palmeri* on sandy ridges, and a fringe of *Allenrolfea occidentalis* at EHW, with occasional *Cressa truxillensis* and patches of *Sarcocornia pacifica*. *Sesuvium portulacastrum* also occurred within sandy areas of the high marsh, with scattered *Limonium californicum* on clayey channel levees. The low marsh water had a normal marine salinity of 35‰ and vegetation comprised c. 50% *Spartina foliosa*, 40% *Sarcocornia pacifica*. No mangroves were found either here or at the large barrier lagoon Laguna Guerro Negro south of Manuela lagoon, despite the climatic potential for shrub mangrove growth as determined by Bardou et al. [25]. Field work in 1973 began in the Mediterranean Sector (Zone I, Figure 2) of the Pacific Coast, and included detailed studies of esteros at La Salina, Punta Banda, Cabo Colnett, and barrier lagoons at Mormona and San Quintin. No mangroves were found there or any coastal sites in Zone I and II north of the Viscaino Peninsula.

Table 2: List of species distributions for 1971-1973 collections. The data in Table 2 include all tidal zones, from the mudflat to the storm tide line above EHW. Mangrove species are in red font; highlight indicates taxa with essentially ubiquitous distributions

	Pacific Coast (n =14 sites)													Gulf Coast	Gulf Coast (n = 10 sites)								
Latitude N	32.5	31.9	30.7	30.4	28.2	26.7	26.8	26.8	26.3	26.1	25.7	24.8	24.4	24.3	24.3	24.1	25.9	28.7	26.6	26.9	28.9	28.9	29.8
Taxon Location	T J	P Ba	Mor	S Q	G N	Ab	E C	S I	S Ju	S G	S. Jo	S. C	P C	P Bal	Pich	L P	Nop	S Ros	B Con	Mul	S L	BlA	B G
Low-Mid Marsh																							
Spartina foliosa	x	x	x	x	x	x	x	x	x	x	x		x										
Salicornia bigelovii	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x					x	x
Batis maritima	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sarcocornia perennis	x	x	x	x	x	x	x	x	x	x	x	x	x				x						x
Suaeda californica	x	x	x	x	x	x	x	x	x	x	x	x	x									x	
Distichlis spicata	x	x		x	?						dune					x		x		x	x	?	
Jaumea carnosa	x	x	x	x																			
Triglochin concinna	x	x		x	x																		
Frankenia grandifolia	x	x	x	x	x																		
Distichlis bajaensis		x	x	x																			
cf. Distichlis littoralis	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						x	x
Sesuvium portulacastrum			x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Laguncularia racemosa						x	x	x	x	x	x	x	x	x	x	x	x		x	x	x		
Rhizophorum mangle						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Avicennia germinans											x	x	x	x	x	x	x	x	x	x	x		
Distichlis palmeri															x						x	x	x
High Marsh																							
Arthrocnemon subterminale	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	X
Limonium californicum	x	x	x	x	x																		
Suaeda cf. S.ramosissima	?						dune		X	x	X		dune			X	X	X	x	x	x	x	
Atriplex frankenioides		x						x			x												x
Cressa truxillensis	x	x	x								x	x	x				x		x		x		
Atriplex julacea		x																					
Iva hayesiana	x																						
Lasthenia glabrata	x																						
Cordylanthus maritimus	x	x	x																				
Lycium californicum	x	?																					
Lycium cf. brevipes		X									x												
Mes. crystallinum	X	X		X					pan														

Mes. nodiflorum	X	X		X																				
Atriplex watsonii	x	x		x																				
Haplopappus venetus	x	x																						
Hordeum jubatum	x	x																						
Parafoliz	x	x																						
Spergularia maritima	x	x		x																				
Salicornia europaea	X	X																						
Heliotropium curassavi.				X																x	x			
Juncus acutus	X			X								x								x				
Frankenia palmeri		x	x	X	x	x	x	x	x	x													x	x
Allenrolfea occidentalis			x			X	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
Atriplex canescens								x	x															
Maytenus phyllanthoides									x	x	x	x	x	x						?	x			
Sporobolus contractus									x	x	X	x			x						X			
Sporobolus virginicus									x				x	x	x	x	x							
Atriplex barclayana											x		beach	playa	x	x		x				x		
Haplopappus v. furfura											x													
Bouteloua aristoides											x		x											
Portulaca oleracea											x													
Suaeda cf. S. californica												x												
Conocarpus erecta												x		x										
Atriplex semibaccata															x									
Prosopis juliflora agg.															x	x	x	x	x	x				
Atriplex sp. (shrub)															x									
Phoenix dactylifera															x	x		x						
Perityle emoryi															dune									
Sarcocornia cf. S. pacifica																x					x	x		
Haplopappus sonoriensis																x		x				dunes		
Cynodon dactylon																				x	x			
Mudflat-subtidal																								
Phyllospadix scouleri										x										x	x			
Phyllospadix torreyi					?					?														
Zostera marina	x	x	x	x	x	x	x	x	x		x								?					
Ruppia maritima						x	x	x			x				?									
Total	29	29	17	21	15	14	14	16	19	16	23	14	18	12	12	18	18	11	15	15	18	13	9	

Climate Zone III

Bahía Asuncion and Laguna Abreojos

In 1972, the northernmost Pacific study site was in the Viscaino Desert-Magdalena Plain Zone III (Figure 2) at Bahía Asuncion (27.707° N, -114.854° W), south of Punta Eugenia at the western tip of the Viscaino Peninsula. At Bahía Asuncion, there were only scattered salt-marsh plants in sheltered rear-dune swales (Figure. 4A) behind a wave-dominated rocky coastline unsuitable for sediment accumulation or mangrove growth. We also established that there was no marsh or mangrove vegetation on the rocky and sandy shore at Bahía Tortugas (27.695° N, -114.899° W),c. 80 km north of Bahía Asuncion.

Figure 4 Archive photos of wetlands at the northern limits of mangroves on the Pacific Coast in 1972. Left panel: Saltmarsh on the rocky coast at Asuncion Bay Cannery, with *Arthrocnemum subterminale* shrubs up to 20 cm high, *Sarcocornia pacifica*, and *Distichlis* grasses; Right panel: Mangroves at Laguna Abreojos, with dwarf *Laguncularia* <1 m, being the same height or shorter than *Spartina foliosa* in 1972. Ed Grainger stands at the site of high marsh soil salinity sample. Gray areas are thickets of drift wood fragments, litter and other plant debris.

At La Bocana, the entrance to Abreojos Lagoon (sometimes called Pond Lagoon or Laguna La Bocana), there was a fringe of dwarf mangrove forest (c. 10% *R. mangle* and *L. racemosa*) along the shore 4.8 km east of the entrance of the long narrow (10 x 2 km) tidal sand-barrier lagoon (Figure 4B). Here the salinity of the fine sandy marsh soil was 35‰, increasing to around 70‰ in poorly drained high marsh areas. The low marsh contained *R. mangle* of the same height (c. 1 m) as the interspersed *Spartina foliosa* that colonised the aggrading mudflats. The *L. racemosa* shrubs were l to 1.5 m high, being largest in the low marsh. Abreojos Lagoon is described in detail as Case History 5.1.1.

Estero del Coyote

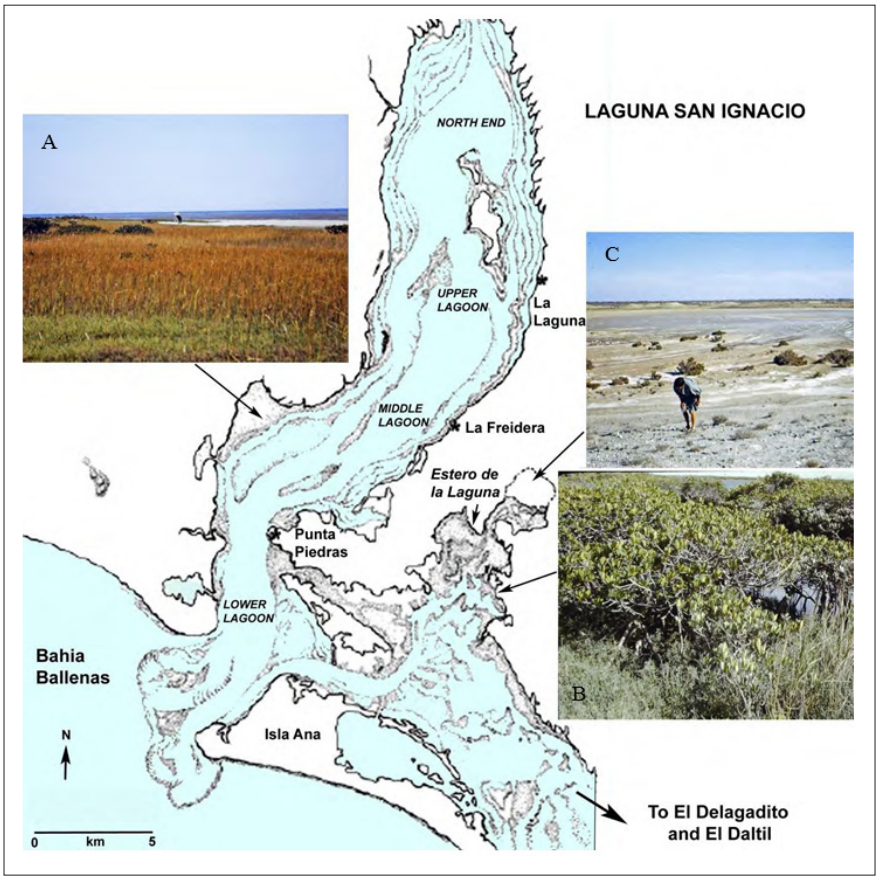
The southern tip of Abreojos Lagoon is the rocky headland of Punta Abreojos. Here the coastline curves west and there is another barrier lagoon 8 km long, called Estero del Coyote or Laguna Escondido (= "hidden lagoon"). Saltmarsh fringed by shrub mangroves occurred along the main channel behind the beach barrier northwest of the lagoon entrance, c. 0.8 km east of Campo René. *R. mangle* up to 2 m high, with many seedlings, occupied the low marsh, together with *Spartina foliosa*. The mangroves fringed an undercut channel above and behind which was high salt-marsh. *L. racemosa* with many germinating seedlings and 1-yr plants were common in the upper low marsh; most of the mature shrubs were c. 1 m high or shorter. *Ruppia maritima* was common in shallow low-marsh ponds and on the mudflats. On the southeast shore of the lagoon, c. 5 km from the entrance, there was saltmarsh behind a narrow fringe of mangroves backed by a low dune ridge. Here, the *Spartina foliosa* was abundant around the edge of a low marsh pond behind the mangroves. On the dune ridge, there were several adventive annuals not seen further north along the coast of Baja California. The case history of Estero del Coyote is documented in Sect. 5.1.2.

Laguna San Ignacio

Estero del Coyote is a northern extension of Laguna San Ignacio which is the second largest lagoon in Baja California: 30 km long, c. 3 – 6.5 km wide, with 25 km-wide entrance area forming a lagoon complex behind the 15 km-long Isla Arena at the mouth (Figure 5). There are also several barrier lagoons inlets further south, at Estero Delgadito and Estero el Dátil [42,57]. The main lagoon drains into Bahía de Ballena and is the remnant of a drowned estuary cut into an ancient seabed overlain by volcanic rocks that crop out as islands and give it an irregular shoreline. The lagoon forms the seaward end of Rio San Ignacio that flows from the mountains about 30 km before disappearing under a sandy arroyo as subsurface freshwater in wet years. Other smaller arroyos drain to the south shore; some of these flow year-round, others are underground springs (Dickey, 1983).

In 1972, there were isolated thickets of shrubby (c. 1.3 m) *R. mangle* (5% cover) and *L. racemosa* (10%) on the NW shore of Laguna San Ignacio (Figure 5A), in the low marsh and shallow channels or ponds. Behind the mangroves, salt-marsh graded to a low dune ridge with *Allenrolfea occidentalis*, beyond which were extensive barren salt flats. *Spartina foliosa* colonised mudflats and dominated the low marsh (50%), with *Ruppia maritima* occurring in channels and ponds of the low marsh. Here and at Estero de la Laguna in the SE, the water salinity was 35‰. Mangrove cover at the more sheltered Estero La Laguna site was greater than in the NW, with c. 35% *R. mangle* and 10% *L. racemosa* in the low marsh, and with sparse (5%) *Spartina foliosa* (Figure 5B). Details are given in Sect. 5.1.3. No collection was made at Estero el Dátil but Gerhard and Gulick reported extensive salt flats with sand dunes (Figure 5C) and a long, narrow lagoon lined by mangroves in places [55]. Dickey (1983) commented that mangroves in the southern San Ignacio lagoons had oysters on their roots.

Figure 5 Sketch map of Laguna San Ignacio (after Lga. SI Ecosystem Science Program, 2015) showing lagoon channels, islands and lagoon barriers, with insets of vegetation seen in 1972. A) NW shore with extensive mudflats and colonising *Spartina foliosa*; B) SE shore with red and white dwarf mangrove; C) extensive salt flats with sparse marsh vegetation behind mangroves.



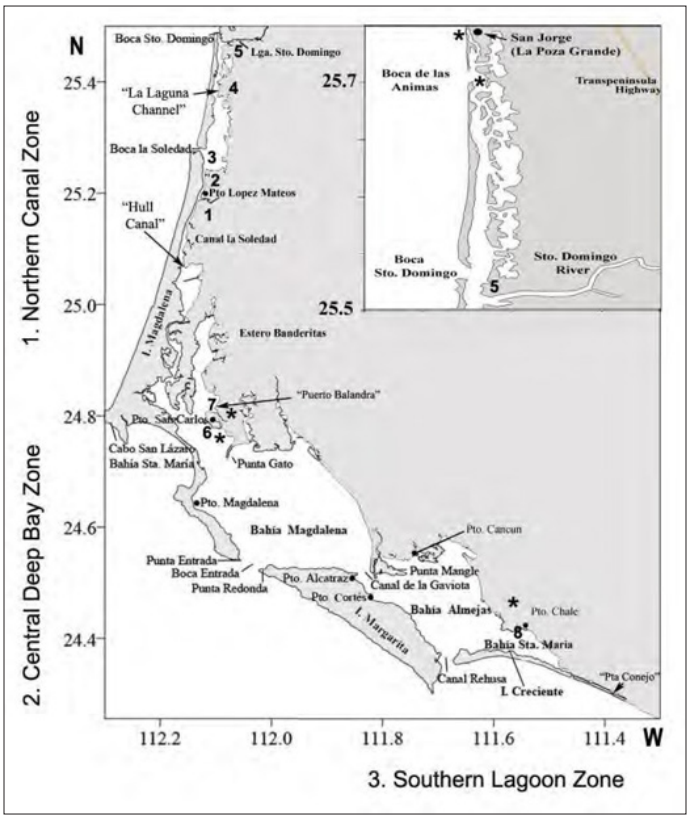
South of the San Ignacio Lagoon complex, Estero del Arroyo San Juan is a drowned estuary behind a tidal lagoon barrier, in front of extensive tidal flats near a fish camp and cannery at San Juanico, in the lee of Punta Pequeña. Here water salinity was 38 – 42‰ and *R. mangle* comprised 25% of the low marsh vegetation cover, being the only mangrove species present.

The soil salinity of mangrove locations ranged from 38 – 42‰, and the height of the dwarf shrubs increased in a landward direction to a maximum height of c. 1 m.

Laguna San Gregorio

Further south, Estero del San Gregorio at the mouth of the La Purisima River is another drowned estuary behind a barrier lagoon with a very narrow tidal channel (= Laguna San Gregorio) resulting in hypersaline lagoon conditions (40 – 60‰) to c. 0.4 km upstream in the river. This site is interesting because Roberts reported that before 1958, the lagoon entrance was wide and the channel was navigable to ships, but chubascos in 1958 and 1959 closed the lagoon entrance with a sand barrier and it remained cut off until at least 1984 [42]. In 2017, Google maps show that the lagoon is again open, at a tourist location now called La Bocana, but there is no visible evidence of mangroves on the mudflats. In 1972, the low saltmarsh was dominated by a low diversity of halophytes — *Batis maritima* (75%), *Distichlis littoralis* and *Sarcocornia pacifica* (25%) — with rare seedlings of *R. mangle* being the only mangroves present. The high marsh contained *Sarcocornia pacifica* with *Batis* and *Spartina foliosa* in wetter areas, the latter being locally abundant at the lower edge. The upper marsh edge was rimmed by *Sesuvium portulacastrum* and *Arthrocnemum subterminalis*. Shrubs of *Maytenus phyllanthoides* up to 3 m high occurred at the edge of the tidal creek, with the roots extending to the mid-tide level. This was the northernmost location for the sweet mangrove at our coastal wetlands study sites: the type locality of this species is in Magdalena Bay.

Figure 6 Map of the Bahía Magdelena-Almejas lagoon complex, modified from Rodrígues et al, with older names inserted for sites studied in 1972. Numbers 1 to 8 are locations visited in 1972; asterisks mark location of photographs in Figures 7, 21, 22. Inset shows locations of Boca de las Animas and San Jorge north of Boca Sto. Domingo that were also visited in 1972.



Bahía Magdalena-Almejas Complex

South of San Gregorio lies the extensive Bahía Magdalena-Almejas lagoon complex that extends from 25.750º to 24.267º N behind a chain of islands. This lagoon-island-estuary complex form one of largest deep water harbors in the world. The whole area (Figure 6) comprises three geomorphologically distinct zones: 1) the Northwestern Canal Zone 112 km long, shallow and navigable to small boats only; 2) the central main lagoon, Bahía Magdalena, ca. 40 x 24 km, with a wide (4 km) entrance and channels 18 – 38 m deep; 3) the southern bay, Bahía Alemas, which shallows at the south end to tidal mud flats at in Bahía Santa Maria near Puerto Chale [58,59]. There have been many studies of the ecosystems and mangroves in this region; therefore details of the 1972 work will only be given for the San Carlos and San Jorge areas (case history Sect. 5.1.3), with a few notes on other localities that marked important floristic boundaries in 1972 [9,59,60].

In 1972, the northernmost Bahía Magdalena-Almejas lagoon complex site we investigated was Estero San Jorge, a barrier lagoon at the mouth of a small river that flows past La Poza Grande c. 6 km to the west. San Jorge is near the beach barrier channel at Boca de las Animas and is connected to both the Pacific Ocean and the La Laguna Channel extending southward to Boca de Soledad. Channel water and soil salinity at San Jorge was 35‰ where *R. mangle* and *L. racemosa* were co-dominant in the low marsh, together with 10% *Spartina foliosa*. In the high marsh, with soil salinity 38‰, we found the northernmost occurrence (5%) of *Avicennia germinans* together with *L. racemosa* (20% cover). Shrub height near the channels was up to 4 m but it decreased landwards to 0.5 m near Mean High High Water (MHHW) where white mangrove dominated, with rare bushes of red mangrove and an undercover of 40% *Batis maritima*. Soil salinity on the adjacent salt flat increased to 58‰ and only succulent halophytes were present except on sandy mounds around EHW where *Allenrolfea* shrubs were interspersed with *Portulaca pilosa, Sporobolus contractus*, and *Atriplex frankenioides*. Similar vegetation was seen at Boca de Soledad which is also located north of a small river mouth. At Boca de las Animas (Figure 7A), there were scattered *Ag* shrubs up to 1 m high on a partly stabilized inlet delta east of the opening in the beach barrier. Black mangrove shrubs were abundant in a poorly- drained swale behind a beach ridge but were only occasionally present on the windward dune slope. On the delta, there were a few dead *Rm* shrubs and abundant aerial roots of *Avicennia* protruded above an eroding peat layer (Figure 7B).

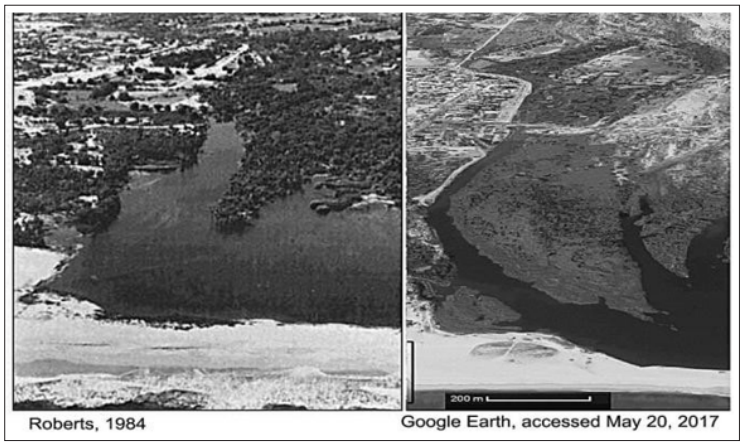
Figure 7 Boca de las Animas North of Central Bahía Magdalena. A) Aerial view, looking north, October 22, 1996 (from John Wark, photographer). B) Landsat view of same area, March 2017 (Google Earth image). C) Exposed peat layers on the delta opposite the channel entrance, April 29, 1972. D) Cow grazing red and white mangrove scrub at Puerto Chale, 1972.

At Puerto Chale in 1972, 1 km south of the main village, there was a fringe of large mangroves (*R. mangle*, 3 m-high and *L. racemosa* up to 4 m-high) in front of low, old dune ridges with shell middens. Behind the tall mangroves bordering the mudflats, *Rm* shrubs were reduced in size (<1 m) and some were grazed by cattle (Figure 7D). Here *Mp* formed a conspicuous shrub zone up to 1 m high near EHW, in front of bare salt flats. *Spartina foliosa* colonised aggrading mudflats in front of *Ag* before being shaded out by the larger mangroves.

Climate Zone IV - Pacific Coast Punta Conejo to San Jose del Cabo

In 1972, no mangroves were seen on the mainland shoreline either at Punta Conejo or in the small brackish ponds (2 – 4‰) behind dunes located 44.6, 35.4 and 12.4 km north of Todos Santos. This area marks the transition from the Magdalena Plain to Arid Tropical Zone IV (Figure 2). A few *Conocarpus erecta* shrubs were found at EHW behind dunes at San Pedrito 23.37° 110.199° W), where there were hypersaline ponds behind the storm berm, fringed by *Arthrocnemum subterminalis* (50%), *Batis maritima* (20%), *Sarcocornia pacifica* and *Distichlis littoralis* (10%). The Buttonwood mangrove was also present at El Palmar, near a hypersaline pond behind a high beach barrier, c. 5 km south of El Pescadero, but was absent at two small brackish ponds behind the beach at Migriño, by the salina on the southeast side of Cabo San Lucas, and at the tidal estuary of San Jose del Cabo (23.065 °N, -109.701 °W). At this southernmost Pacific mangrove location, in 1972 there was a tidal estuary at the mouth of the San Jose River and hypersaline ponds behind the beach berm. The estuary was fringed by 50% *Lr* and *Rm*, with occasional shrubby *Ag* and an undercover of *Suaeda torreyana* and *Batis*. Roberts (1984) noted that by 1978, the river flowed only during flood intervals because of heavy agricultural and urban water use. His aerial photograph displays a larger water area and greater vegetation cover on the delta lobes than is seen in 2017 (Figure 8).

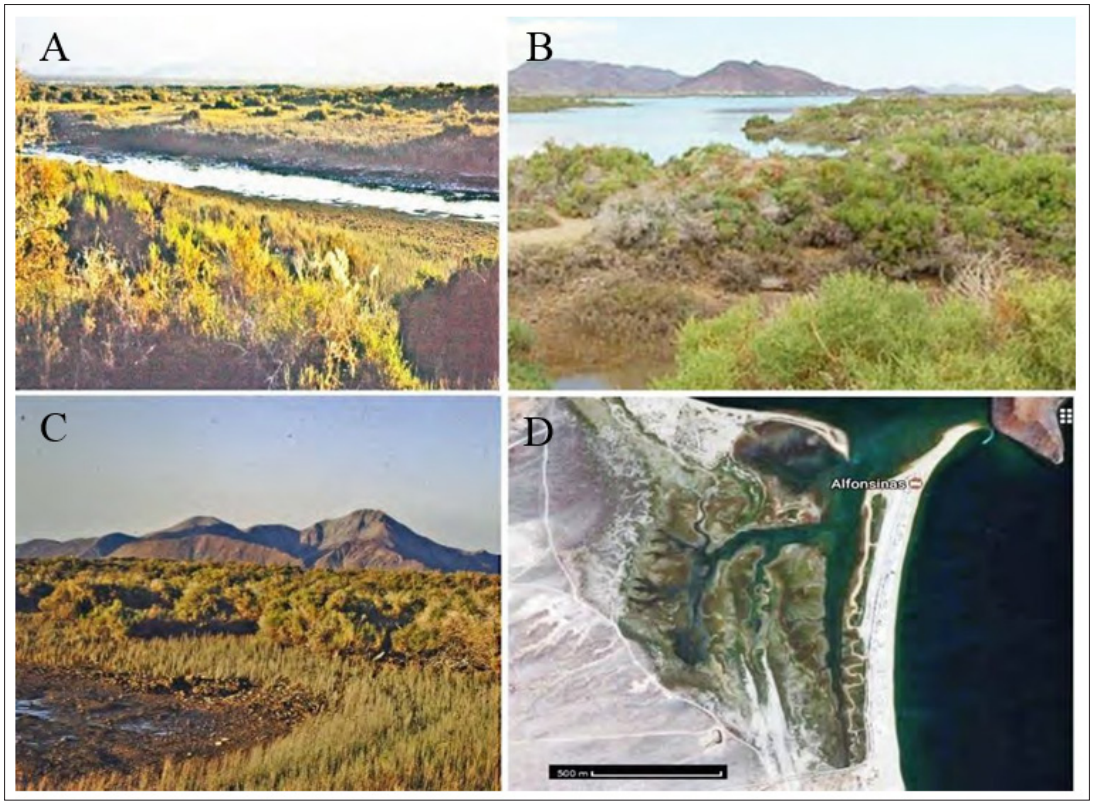
Figure 8 Estero San Jose del Cabo comparison, looking NW. Left: image from Roberts; Right: 2017 Google Earth image, accessed May 20, 2017 [42]. There is a major (>50%) reduction in vegetation cover on the delta lobes and west shore, and a large aggradation of the mudflats.



Gulf Coast Studies in 1972–1973
Climate Zone VI

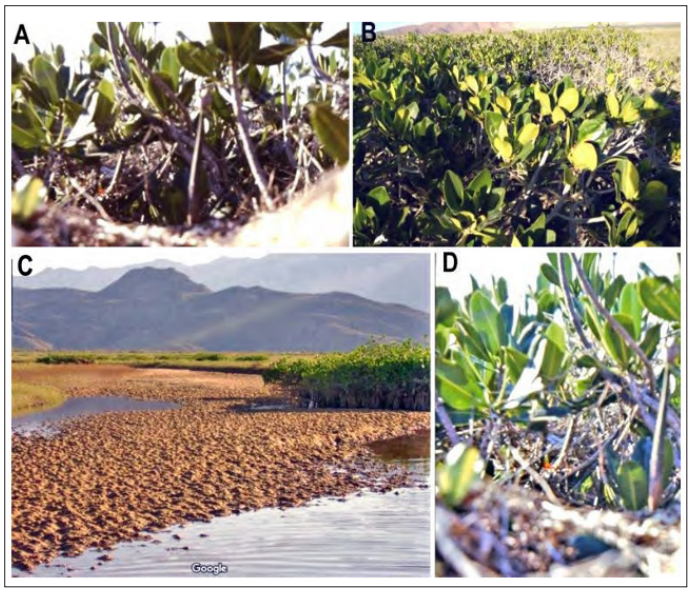
Bahía San Luis Gonzaga and Bahía de Los Ángeles
In 1972, field work began on the Gulf Coast of Baja California in Zone VI (Figure 2) at El Huerfanito (30.116 °N, -114.623 °W) about 53 km. north of Alfonsina's restaurant on Bahía San Luis Gonzaga (a.k.a. Gonzaga Bay), in the Micropyllous Desert subregion of Wiggins [16]. At this site, a large saline swale behind the beach berm was dominated by shrubby *Allenrolfea occidentalis* and *Frankenia palmeri*, with sub-dominant *Suaeda* cf. *linearis*; soil salinity was high, to c. 105 ‰. No tidal zonation was discerned and no mangroves were seen either there or at Bahía San Luis Gonzaga (Figure 9), near Alfonsina's restaurant where there is a tidal inlet (estero) behind a beach barrier at the northern edge of a large bajada. On the east bank of the main tidal channel at Alfonsina's Camp, *A. occidentalis* dominated on sandy ridges around Extreme High Water (EHW), with an undercover of *Sarcocornia subterminalis* and *Atriplex* cf. *cansecens*. Sub- dominant *F. palmeri* and *Atriplex barclayana*. *Salicornia bigelovii* occupied damp saline swales between the ridges. The low marsh was dominated by *S. subterminalis* with infrequent *F. palmeri*, and on the mudflats, was co-dominant with *Salicornia bigelowii*.

Figure 9 Estero at Gonzaga Bay in 1972 (A, C), in 2008 (B) and in 2017 (D). This salt-marsh is only c.170 km north of Bahía de los Ángeles and seems to have suitable conditions for scrub mangrove growth [25]. However, so far there is no evidence of northward mangrove migration. Airplanes park next to cottages along the road to Alfonsina's hotel after landing on the sand spit that is a runway and road although flooded at highest tides.



In 1973, most field work focussed on sites along the Gulf Coast from Gonzaga Bay to La Ribera in the Cape region. A repeat visit to Gonzaga Bay again failed to locate any mangroves. However, shrubby *R. mangle* was found at in Bahía de los Ángeles (Figure 10), c.100 km further south, in the lee of Isla Ángel de la Guarda and several smaller islands, e.g. Isla Smith (a.k.a. Is. Coronado), at the mouth of the deepwater lagoon. Most of the shoreline around the bay consists of coalescing bajada deposits or volcanic outcrops unsuitable for establishment of tidal wetland vegetation. However, mangroves were found in the tidal lagoons behind extensive sand barriers in Estero La Mona at the south end of the bay. Two small copses of 20 – 40 *R. mangle* shrubs <1 m-high occurred in the estuary, and another grew behind a gravel bar enclosing a cove southwest of La Mona. Details of this site are given in case history 5.2.1. A gravelly salt-marsh site further north on the west shore of Bahía de los Ángeles, c. 3.3 km south of hotel Casa Diaz 29.041° N, -113.549° W, however, contained no mangroves. Here *Frankenia palmeri* and *Allenrolfea* were the main halophytes, with common *Lycium* cf. *brevipes* growing just above EHW. Central Bahía de los Ángeles marks the border between southern end of Zone VI with <100 mm annual precipitation and the central Gulf Coast subregion V which has c. 100 – 150 mm per year and warmer summers.

Figure 10 Bahía de Los Ángeles comparison 1973 to 2013 images. A and D): archive images of dwarf red mangroves (<1 m) at Estero La Mona 1973, with abundant seaweed litter (A) and with relatively large propagules c. 20 cm long (D). B) dwarf red mangrove at La Mona in 2013 (courtesy I.C. Feller); C) Taller red mangroves (c. 1.5 m) at El Rincon in 2008 (Google Earth Panoramio image).



Climate Zone V

Bahía San Lucas and Mulejé

At Bahía San Lucas, c. 27.222° N, c. 24 km south of Sta Rosalia in northern Zone V, there were tidal estuaries at the mouths of arroyos and scattered saline ponds behind low sandy beach ridges in the lee of San Marcos Island. Here we found c. 20% cover of *R. mangle* and *A. germinans* along the tidal channels, with 50% *Arthrocnemum subterminalis* and *Suaeda* cf. *californica* bordering the salt ponds,with 30% *Cyperus laevigatus* and *Cynodon dactylon* in brackish ponds behind the beach ridge, below a grove of date palms. This was the northernmost accessible site in where we found black mangrove in 1972, and also the northernmost location for the saltmarsh grasses *Sporobolus virginicus* and *Sporobolus pyramidatus*. However, near San Bruno (27.171° N), c. 41 km N of Mulejé, there were extensive barrier lagoons and ponds of brackish water behind a low beach berm, but no mangroves were present in 1972. In contrast, González-Zamarones et al, reported A [51]. *germinans* for Las Animas near Bahía de Los Angeles and for Bahía de San Rafael (28.452 °N,-112.982°W), at Ensenada Las Palomas (location unknown), at Bahía San Carlos (27.862° N,-112.642° W between B. de los Angeles and B. San Lucas (Figure 2), and at Bahía Sta. Ynez (c. 26.979° N) immediately north of Mulejé. Mulejé is the northernmost of several estuaries at the mouths of large rivers discharging to the Gulf Coast from 26.89° N to c. 25.931° N, near Nopoló. Much of the Mulejé shoreline has long been cleared for farming and date palm plantations but shrubby red and white mangroves and some black mangrove still colonize mudflats and shorelines, including the inner beach barrier linking the northern shore to the lighthouse island.

Bahía Concepción

Located about 20 km south of Mulejé, Bahía Concepción is a broad, deep lagoon, c. 40 km long. Most of the bay shoreline is steep-sided volcanic terrain and is almost inaccessible except for a few small sandy coves on the west shore and a salina at the south end. Gerhard and Gulick reported mangroves at Santispac near the northwest entrance to the bay, but these were not seen in 1972 – 1973 [55]. Conversely, Gerhard and Gulick did not mention mangroves at El Coyote where we surveyed the mangroves in tidal channels and coves behind sheltered headlands [55]. Here the channel water had a normal salinity of 35‰ and *A. germinans* was dominant (c. 50%) with 20% *R. mangle* and c. 10% *L. racemosa* in the low marsh and c. 20% *Batis* and *Arthrocnemum subterminalis* in the high marsh. At a location now called Playa Armenta, there was a white sand beach behind which there was *Maytenus* and *Batis* but no other mangroves in 1972. In contrast, at a cove near El Requéson c. 1 km further north which was protected by a cobble beach, white mangroves fringed the saltmarsh with *Allenrolfea*, *Sarcocornia, Salicornia* and *Batis*. At Santa Rosalillita, (now the campsite Santa Rosalita in southern Bahía Concepción), there were salinas and intermittent tidal channels behind low beach ridges. Here Batis maritima (50%) and *Arthrocnemum subtermimalis* (40%) were co-dominant, with a small amount of *Sarcocornia pacifica* and rare dwarf *Avicennia germinans*. Details are given in Case History 5.2.3 for this entire area which now has three sites designated as being of national concern for conservation.

Loreto-Nopoló

South of Concepción Bay, much of the shoreline is rocky but *Rhizophora* and *Laguncularia* were seen at Loreto, behind the sandbar of the Arroyo de La Parras estuary (a.k.a Arroyo San Telmo), and at other sites on the shore of Loreto Bay. Much of Loreto area was urbanised by 1973 and mangrove cover was sparse. However, at Nopoló ca. 8 km further south, shrubby mangroves covered an area of c. 20 ha in a small tidal lagoon behind a barrier beach and a rocky headland. Here the main channel (salinity 35‰) was fringed by extensive thickets of *Rhizophora and Laguncularia*, behind which a narrow border of saltmarsh graded upwards to a broad salt flat. *A. germinans* was dominant (50%) with a mixture of *L. racemosa* and *R. mangle* (40%) along the channels; *Batis* and *Sarcocornia subterminalis* (10%) were the main salt-marsh species on the upper margins of the channels. These sites and other smaller mangrove areas at San Bruno, Puerto Escondido and El Juncalito (González-Zamorano et al., 2011) are now protected within the Bahía de Loreto National Park and will be discussed further as Case History 5.2.4.

Climate Zone IV - Gulf Coast

The remainder of Gulf Coast sites surveyed in 1972 and 1973 were in the Cape Region (Zone IV), particularly in the vicinity of La Paz. Here many studies have recently been made of the mangrove populations on El Mogote, the sandspit enclosing the inner bay, and in eastern bay coves, e.g. El Conchalito, Bahía Pichilingue and Punta Balandra [19-21]. Although Bahía de La Paz was discovered by Hermán Cortéz in 1533 and periodically visited by Spanish pearl- hunters, it was not settled by missionaries until 1720 and it remained essentially uninhabited until 1811 when farming began on former mission property [55,58]. Thereafter, fishing and pearl-harvesting were the main industries, supporting a population of c. 400 by the time it became the state capital in 1830 after Loreto was wiped out by a storm in 1829. Following occupation of American troops in 1874 and development of ore mining inland by 1862, the population rose to 10,000 by 1874. However, almost a century later (in 1960), the population had only doubled to 23,324 and it was probably this size in 1972 and 1973 [55]. In contrast, today, La Paz has a population >10 times larger (238,8000). The >impact of urbanization at La Paz is discussed in several recent papers: here we provide some baseline data areas included in our 1972 – 73 surveys [19,21,53].

In 1972, we made a survey at the site of the radio station c. 19 km west of Hotel La Perla in downtown La Paz, near the current location of CIBNOR (Centro de Investigiones Biológicas del Noroeste). Here there was a fringe of red and white mangrove along the shoreline, behind which was a border of black mangrove, in places dying after being flooding by ponded water as a result of road construction (see Figure 7.42) [14]. The high marsh beyond the mangrove contained *Arthrocneum subterminalis* and *Sarcornia pacifica* in elevated areas, with shrubs of *Suaeda ramosissima* (up to 1.7 m high) and *Maytenus phyllanthoides* to c. 3 m. The salt flat was bordered by *Allenrolfea occidentalis* and *Sporobolus virginicus*.

In Bahía Pichilingue c.5 km west of La Paz, there was a deep-water harbor behind Isla San Juan Nepamueceno, with mangroves, channels and ponds covering a total c. 25 km^2 on the mainland shore. Channels behind sandy beaches at the north end are now closed by the ferry terminal and other developments. This bay may have been the site of earliest colonial settlement (1535) in the La Paz region, and it was a coaling station for the US Navy from 1866 –1925, yet it was largely uninhabited in 1972. We surveyed at a tidal lagoon now called Estero Puerto Gato at the south end of the bay, c. 5 km west of the Pichilingue ferry terminus. The water salinity was 35‰ and thickets or fringes of mangroves bordered extensive calcareous sandy tidal flats, backed by a narrow zone of salt-marsh grading upwards into a barren salt-flat just above EHW with common *Allenrolfea*. The 1972 transects included *Avicennia* (c. 25%, shrubs to 2 m) behind a forest fringe with *Rhizophora* dominant (20 – 50%) and *Laguncularia* (20%) up to 5 m high along the channel and co-dominant around MHHW. In the low marsh, there was an undercover of *Batis* (25%) and minor amounts (10%) of other saltmarsh succulents and grasses, e.g. *Arthrocnemum* and *Distichlis littoralis*, with *Sporobolus virginicus* on sandy berms. About 1 km south of this site, other similar mangrove areas seen in 1973 are now replaced by beach resorts or, less commonly, by industrial development sites. At most sites, the highway has reduced tidal exchange to the upper marsh, and in 2014, the *Avicennia germinans* was reduced in size and extent.

In 1973, a survey was made of mangroves in woodland behind the extensive, shelly sandbar now called Balandra Beach in the rocky cove of Bahía Puerto Balandra, 11.3 km northeast of Pichilingue. Here there was a mangrove shrub forest (total area c. 25 km^2) surrounded by salt- flats in a tidal lagoon of normal marine salinity. Located at the end of a remote road, today this wetland remains the only largely undisturbed area in the La Paz region and since 2008, an area of 4.89 km^2 has been protected as a Ramsar Wetlands preserve. In 1973, *Rhizophora* and *Laguncularia* comprised 30% of the cover in the lower tidal areas, surrounded by c. 30% *Avicennia*, with the remaining area covered by salt-marsh including 20% *Batis maritima*, and 20% *Sarcocornia virginica* + *Suaeda californica*. A notable feature of this site was the extensive shell mounds exposed on the inner beach barrier above the mangrove fringe, and the presence of tropical herbs (*Amaranthus watsonii*, *Krameria canescens* var. *paucifolia, Ditaxis linearis*) that were not found at the other study sites. This mangrove site is now a baseline reference study area for Gulf Coast mangrove protection [60].

The southernmost Gulf Coast study site in 1972 – 1973 was at La Ribera 23.593° N, -109.590° W, c. 100 km south of La Paz on the road to Punta Colorada. Here there was a brackish pond with *Pistia stratiotes, Sporobolus pyramidatus, Distichlis spicata, Distichlis littoralis, Eragrostis amabilis*, and several sedges (see Appendix 1) near an abandoned hacienda on the margin of Arroyo Santiago. A hypersaline pond was also found behind a beach barrier located 7.24 km south of La Ribera. Here there was saltmarsh with 10% Conocarpus, 50% *Batis*, 20% *Sarcocornia pacifica*, 10 % *Distichlis littoralis*, 10% *Arthrocnemum* + *Sporobolus virginicus*. Shrubby *Atriplex barclayana* and *Suaeda ramosissima* were also present, but no other mangroves. In 1973, the La Ribera-Cabo Pulmo area was a small village supported by the ranching of goats, cattle and chickens, fishing and pearl fishing. However, after about 2002 when the Los Cabos area became commercialized, many American settlers relocated to the eastern Cape region, in search of unspoiled natural environments — their version of Paradise. As a result, the Mexican population of c. 80 dwindled, the American population increased to c. 1500, and in 2006, developers purchased 800 acres from the pueblo, including the boat ramps and a long sectionof beach [61]. The development plan, opposed by most residents, was for a marina, golf courses, many hotels and condominiums, and is manifest today as the resort of Vista La Ribera (Figure 11).

Figure 11: Although the planned 2012 Cabo Riviera project failed, by 2017 the coastline was completely altered by the Vista La Ribera development. Aerial photograph is from http://www.vistalaribera.com/la-ribera/.

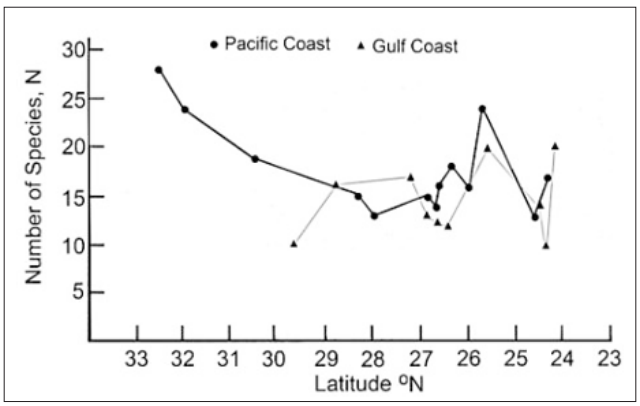
This case history, documented in detail by Anderson (2014) exemplifies the way in which most wetland areas of the BCS Cape and Gulf coasts have been diminished in the 21st C, largely following paving of dirt roads that previously isolated the villages and natural areas.

Analysis of 1972–74 Field Data

The 1972–1973 collections and studies were made primarily to understand patterns of biodiversity with latitude on the coasts of Baja California, following the phytogeographic approach of Johnson [56]. Table 2 lists the latitudinal ranges for all the surveys and tidal zones within the wetlands but excluding the non-tidal brackish ponds in the Cape Region reported in Section 4.2. Appendix 1 provides further details for species.

The floral distributions show that c.10% of the 63 tidal wetlands taxa are present at essentially all sites. The ubiquitous taxa comprise five succulent halophytes (*Salicornia bigelovii*, *Batis maritima*, *Sesuvium portulacastrum, Arthrocnemum subterminalis*, and *Allenrolfea occidentalis*), and two salt-excreting grasses (*Distichlis spicata, D.littoralis*). There are notably fewer taxa (n = 16) in the low to middle marsh than in the high marsh habitats which includes adventive plants at the storm tide line. Of this low to middle marsh group there is a cluster of four taxa that do not extend south of the Viscaino Peninsula: *Jaumea carnosa*, *Triglochin concinna, Frankenia grandifolia* and *Distichlis bajaensis*. The endemic salt grass *Distichlis bajaensis* is the most restricted of this group, occurring at only three sites in Zone I; its Gulf Coast counterpart *Distichlis palmeri* is also restricted in distribution: three sites in Zone VI and one in Zone IV. The mangrove taxa are confined to latitudes south of c. 27° N (Pacific Coast) and 29° N (Gulf Coast). The high marsh herbaceous taxa show more widespread distributions except for a diverse cluster of annuals and suffrutices confined to Zone I, and a smaller cluster exclusively in Zone IV between c. 24° and 25.7° N. Species diversity (N) is similar on both coasts (Figure 12) but is slightly lower (N = 10 – 20) on the Gulf Coast than the Pacific Coast (N = 13 – 27). It is notable that the greatest difference in tidal wetlands plant diversity for the two coasts occurs in the latitudes above 29° N, where the mangroves disappear. From 29 – 33°N, on the moister, cooler Pacific Coast, there is a steep diversity increase whereas diversity decreases on the dry, hot Gulf Coast.

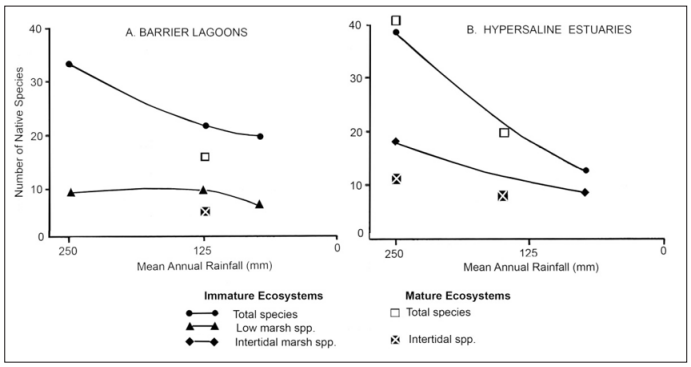
Figure 12 Changes in total species diversity (N) with latitude for 58 intertidal wetlands on the Pacific and Gulf Coasts of the Baja California Peninsula in 1972–3.



The geomorphology and maturity of wetland environments influences the average salinity of tidal channels and soil microtopography, in addition to the amount of space available for colonization [13,51,62]. We therefore examined the diversity of the Pacific coastal wetland species in barrier lagoons with normal marine salinity compared to the estuaries that are hypersaline in this arid climatic region (Figures 13A and B). Floral diversity was also compared to mean annual rainfall records from the nearest coastal weather stations. For these comparisons, we excluded non-native invasive species in the high marsh. Results show there was a large (c. 50%) decrease in diversity with rainfall within both geoforms. The barrier lagoons supported a lower diversity compared to the estuaries, for both the young and the mature systems. The lagoon low marshes contained notably fewer species, especially within the mature, largely sediment-filled ecosystems.

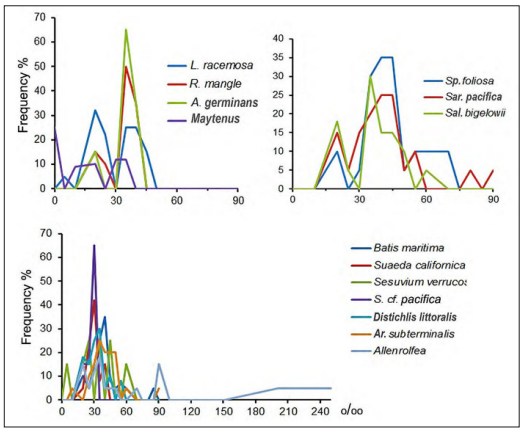
Hypersaline estuaries showed less difference between youthful and mature ecosystems but a greater sensitivity to annual precipitation as expected for environments shaped by river runoff. Regardless of geoform and marsh habitat, however, the fewest native species coincided with the lowest level of precipitation (49.9 mm) in the Pacific hypersaline estuaries.

Figures 13 Changes in floristic diversity versus mean annual rainfall for five Pacific Coast sites representative of different geoforms: A) barrier lagoon, and B) estuarine wetland systems in Baja California. Non-native invasive species are excluded from this data-set.



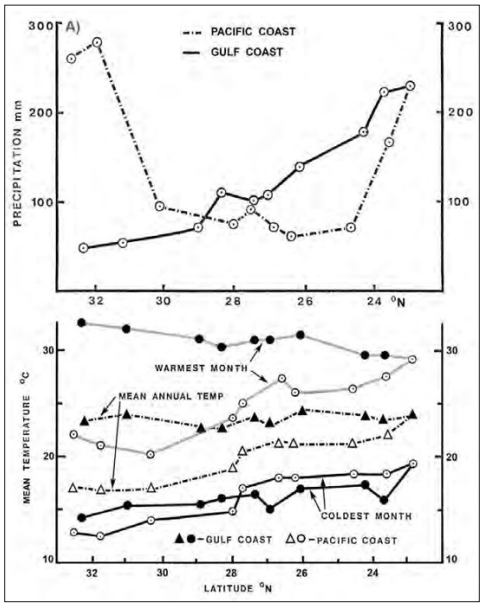
Soil salinity data collected in 1972/73 (Figure 14) show that the herbaceous species in the low marsh zone had a range of associated salinities from 20 to 90‰, with highest relative abundances occurring at 40–45‰. This wide range of salt tolerance reflects the conditions in hypersaline estuaries with periodic changes from brackish to excessively high salinities, depending on river discharge and/or closure of the estuary entrance. In contrast, the mangrove shrubs had a lower range of soil salinities from freshwater to 45‰, with maximum % abundance for *R. mangle* and *A. germinans* at 35‰, and with lower salinity values for the maxima of *L. racemosa* and *Maytenus*. Maximum % abundances of the dominant middle and high marsh species tend to occupy successively higher positions from 30‰ (*Sarcocornia* cf. *pacifica*) to 40‰ (*Batis maritima*), with some taxa showing smaller peaks up to 90‰ (*Allenrolfea occidentalis, Arthrocnemum subterminalis, Batis*), and with *Allenrolfea* being present at salinities up to 250%.

Figure 14 Soil water salinities measured for wetlands species in the Baja California marshes from 1972–73. The average number of sites measured per species was 18, ranging from 6 (for *Avicennia germinans*) to 41 (for *Batis maritima*). Full names of taxa are given in Table 2.



Temperature and precipitation data were examined to better understand the restricted distribution of the mangrove species compared to the saltmarsh taxa, and to explain the asymmetrical occurrences of the dominant taxa *R. mangle, L. racemosa* and *A. germinans* on the Pacific and Gulf coasts (Figure 2). In 1975, annual total precipitation decreased from highs of 236 mm (Cabo San Lucas) and 224 mm (La Ribera) on the Pacific and Gulf coasts, respectively, to corresponding lows of 49.9 (Punta Conejo) and 48.8 mm (San Luis Gonzaga). However, the latitudinal distribution of average rainfall differed on the two coasts. On the Gulf Coast, there was a gradual northward decrease in rainfall while the Pacific Coast was characterised by a rapid drop in rainfall north of the Cape region (Zone IV, Figure 2), followed by a steep rise to the north between Guerro Negro (79.8 mm) and San Quintin (142 mm). This difference is largely related to the seasonal distribution of rain. In Zone IV, there is a large summer peak in rainfall from tropical storms during the Mediterranean climate (Zones I and II); dry seasons where the rainfall maxima are in fall and winter Figure 2). There is no equivalent winter rain increase northward along the Gulf Coast (Figure 15A) [56].

Figure 15 Climatic data for coastal Baja California to 1975. A) Distribution of mean annual precipitation; B) Mean annual precipitation for annual averages, warmest and coolest months.



Mean annual temperatures and average values for the warmest months also differ on the two coasts but there is less difference for the coldest months (Figure 15B). Most notably, summer maxima on the Gulf Coast show a slight rise (c. 29 – 33°C) from south to north while the corresponding Pacific Coast values decrease by about 10°C. Mean annual temperature also declines strongly towards the north on the Pacific Coast but varies little on the Gulf Coast.

Average values for the coldest months are above 12°C for both coasts but they drop more abruptly around 27° N near the Pacific Coast mangrove limit than on the Gulf Coast where they remain at 15°C or higher as far north as 29° N.

Further information regarding the climatic factors driving the three main Baja California mangrove shrub distributions come from examining their dispersal in a Venn diagram (Figure 16) of mean annual temperature (T_{ann}) vs. precipitation (P_{ann}). This graph shows that the mangroves are confined to regions with T_{ann} >20°C. In contrast, all the Pacific sites with only saltmarsh vegetation are in cooler areas (T_{ann} <19 °C) of Zones I and II, with the Zone I/II separation corresponding to P_{ann} >250 mm and < 150 mm, respectively. Gulf Coast sites with only saltmarsh taxa are all located in the warmest sector (c. 23 – 25°C) and are mostly in the driest area of Zone VI where a single site with only *A. germinans* occurs at Puerto Lobos, Sonoran Mexico. *A. germinans* also occurred as the sole mangrove at one site on the BC Peninsula, at Sta. Rosaliita, Bahía Concepción, in the slightly moister Gulf sector of Zone V. However, the Zone V cluster is the most variable, including wetlands with either *Rm* + *Ag* or *Rm*+ *Lr*. The wettest Gulf sector (Zone IV) also had *Rm* + *Ag*. The Pacific Coast Zone III occupies an arid region (P_{ann} 50 – 100 mm) with intermediate T_{ann} (20 – 22°C). Here *Rm* and *Lr* alone are on the cooler side compared to Pacific occurrences of *Rm* + *Ag*.

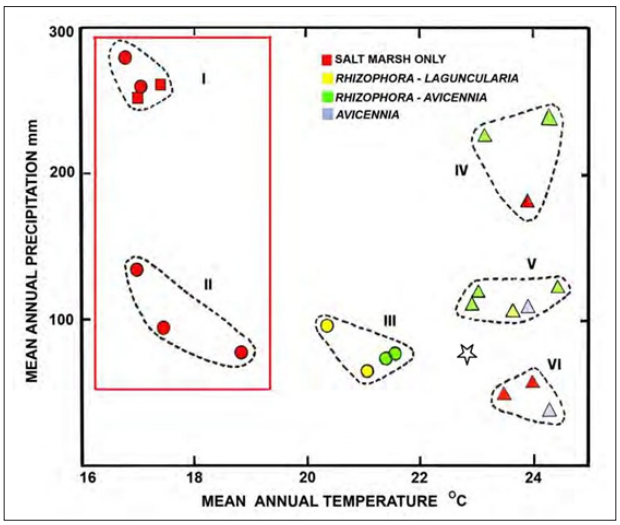


Figure 16: Temperature-precipitation plots of 22 tidal wetlands in Baja California in 1974, showing distributions of saltmarsh versus mangrove vegetation for the Pacific Coast (circles and squares) and the Gulf Coast (triangles) which here includes one site at Puerto Lobos in Sonora.

The star marks the parameters of the boundary between Gulf Coast Zones V and VI.

Selected Case Histories

In this section, we document the salient changes in scrub mangrove

vegetation that have occurred between the 1970's field surveys and the past two decades (c. 1995 – 2017), as determined from historical accounts, aerial photographs and Google Earth images. First, we provide case histories of mangrove changes from selected sites on the Pacific Coast in Zone III where population and industrialization is mostly low in the coastal area, and where land-use change from 1978 – 2000 has been relatively small [63]. Secondly, we examine changes at selected sites on the Gulf Coast from the low population area Zone VI to the most populated and altered locations in Zone V).

Pacific Coast

All these sites are Zone III but the northernmost location, Laguna Abreojos is near the transition from winter to summer rain while the southernmost site at San Carlos is near the subtropical- tropical boundary. The sites from San Ignacio Lagoon northwards are in the El Vizcaíno Biosphere Reserve created in 1988 and they are part of the CONABIO mangrove protection site PN07 [64].

La Bocana de Laguna Abreojos (Pond Inlet)

The northernmost Pacific Coast site of mangroves is at Laguna Abreojos, c. 26.71° N. This barrier beach lagoon is in one of the least populated coastal areas on the Pacific Coast of Baja California and therefore an important baseline for monitoring natural ecological changes over the 45 years since 1973.

There is no fluvial drainage to this southern Sonoran Desert lagoon, and the shallow (<6 m) entrance channel prevents entry by large vessels. The earliest Spanish missionaries (c. 1728 – 1840) reported that the area was not permanently inhabited because of a lack of fresh water, and they did not establish a church or ranch there [58]. La Bocana de Laguna Abreojos probably first came to attention of colonists during Scammon's whaling expedition in San Ignacio lagoon 1859 – 60. However, there appears to have been no pre-1940 development here although in neighboring Turtle Bay a Japanese businessman employed the local fishermen to work in lobster and abalone fisheries [65]. The fish camp of La Bocana was uninhabited in 1961 and in 1972, at which time the site was only accessible by boat or rough dirt road. During the 1960's, however, there was a temporary village with 30 houses and several fish processing plants [58,65]. In 1996, La Bocana and Pta. Abreojos were linked to San Ignacio by a graded road, and the mainland shore was crossed by many dirt side-roads and a small plane landing strip (Figure 17A) used by tourists, sport-fishermen and for commercial salt harvesting [66].

By 2004, a small port developed with a medium to high-intensity fishing industry supporting 2000 inhabitants, including the neighbouring village of Pta Abreojos [67]. In 2020, the La Bocana population was c. 1000, supported by a fishing co-operative and a small tourist industry that began around 2000.

The earliest detailed record of mangroves at this site seems to be that of the ornithologist Laurence Huey who reported that the wind-blown western beach barrier had no vegetation whereas the mainland shore was covered by mangrove thickets interspersed with areas of *Spartina*. He noted that the mangroves did not extend the whole length of the lagoon but only to the tidal limit about 9.7 km from the shallow entrance. The eastern section of the lagoon was described as being "one large slough that winds about, snake-like, through a Salicornia marsh".

This 1927 description is little different from what can be seen in aerial and satellite images for 1996 and 2017 (Figure 17A, B), with the main difference being the migration of mangroves along the inner edges of the sandy beach barrier by 2017, increasing the areal coverage. In 1972, we estimated mangrove coverage of c. 5 km^2 which is very close to the area of 4.9 km^2 given for Google-Earth images in 2006 [51]. López-Medellín et al. also showed no areal change between 1978 and 2010 [64]. Comparison of archival images from 1972 and 2013 (Figures 1, 17C, D) shows little change (~15%) in marsh vegetation extent but importantly reveals a >50% increase in canopy height. The 1972 data show maximum heights of 1 m for *R. mangle* and 1.5 m for *L. racemosa* (Figures 17 C, D). The archive images also show large amounts of *Zostera* and other debris on the dwarf mangroves in addition to abundant leaf litter (Figures 17 E,D). In 2013, there was about the same amount of litter on the mudflats (images of I. C. Feller, Smithsonian Inst.) but little evidence of debris on the shrubs. López-Medellín and Ezcurra also reported a 25% decrease in dead mangroves at La Bocana from c. 1972 to 2009 [67]. In 2013, the white and red fringe mangroves were notably taller, up to c. 2 m, than in 1972 (Figures 17E, F), although some shrubs had leaf and propagule damage. It is most likely that the debris in the mangrove tops reflects the effects of a large storm: the 1972 survey was made in the spring after tropical cyclone René-Olivia made landfall at Laguna Abreojos in September 1971. This was the first tracked hurricane known to cross from the Atlantic to the Pacific Ocean, and it reached speeds up to 185 km/hr.

Figures 17: Comparison of mangroves at Laguna Abreojos 1972 to 2017. A) 1996 aerial photo (John Wark, with permission). B) Google-Earth image, June 2017. C) 1972 image of *L. racemosa* (yellow foliage) in middle marsh, almost covered in debris (white strands). D) 1972 image of dwarf R. mangle in mangrove fringe (scale as in C). E) *L. racemosa* in mid-marsh, 2013, F). Low marsh with *R. mangle*, 2013. Scale in C and E is 100 cm.

Estero del Coyote and Laguna San Ignacio

San Ignacio (Figure 5) is the second largest lagoon in Baja California and has a 3 km-wide entrance and a deep entrance channel (up to 17 m) that allows the entry of large ships from Bahía de Ballenas [42,64]. This V-shaped main channel marks the large estuary of Rio San Ignacio that was formerly connected to Estero del Coyote 16 km to the northwest. In 2020, Estero del Coyote is an isolated, 8 km-long, shallow (2 – 4 m) barrier lagoon almost filled with mangrove-covered sand bars (Figure 21). South of the

main part of San Ignacio Lagoon, a large island separates two channels that drain into Bahía de Ballenas. Further south, there is a string of narrow coastal barrier lagoons, including Esteros La Laguna, Delgadito and el Dátil.

Similar to the Laguna Abreojos history, the first missionaries wrote that the entire San Ignacio area was sparsely inhabited [58]. Smallpox epidemics further reduced the population, so the few survivors were relocated to the Mission at San Ignacio c. 45 km inland. After the Jesuit expulsion in 1767, former mission employees started cattle ranches, fruit and date farms along the river, and they used the lagoons to supplement their diet. Bahía de Ballenas (= Bay of Whales) was named by Vizcaíno in 1542 but commercial whaling did not begin until 1859 when fishing camps were set up near freshwater springs around the lagoon. However, the settlers left about a decade later when the whale population was decimated. Small-scale fishing resumed and the lagoon region remained inhabited except for a short interval of the turtle harvesting in the early 20th C. Larger-scale economic development began in the 1940' s and in the early 70's, fishing ejidos (co-ops) were established along the southern shores of the lagoon, at La Laguna and El Almacen, followed by tourist whale-watching after 1978. By 2004, the population of Laguna San Ignacio was 1,000 [67].

At Estero del Coyote in 1971, there were a few residents living near the channel entrance and at Campo René, a seasonal fishing camp (Figure 21). Today, there is an important regional fishing co-operative at Pt. Abreojos. For 73 years, the industry was based on the Japanese-sponsored lobster, abalone and clam industries but in the1980s, the ejidos amalgamated by the Mexican government and diversified to fin-fishing [66,68]. In 2004, houses, hotels and restaurants developed for a tourist industry although the population remained small (15 at Campo René, with 788 residents at Pta. Abreojos in 2010).

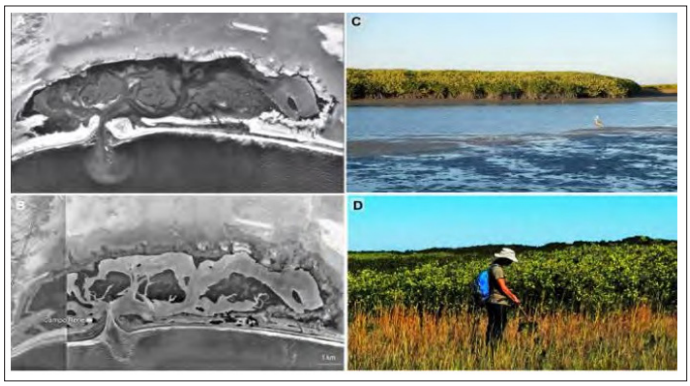
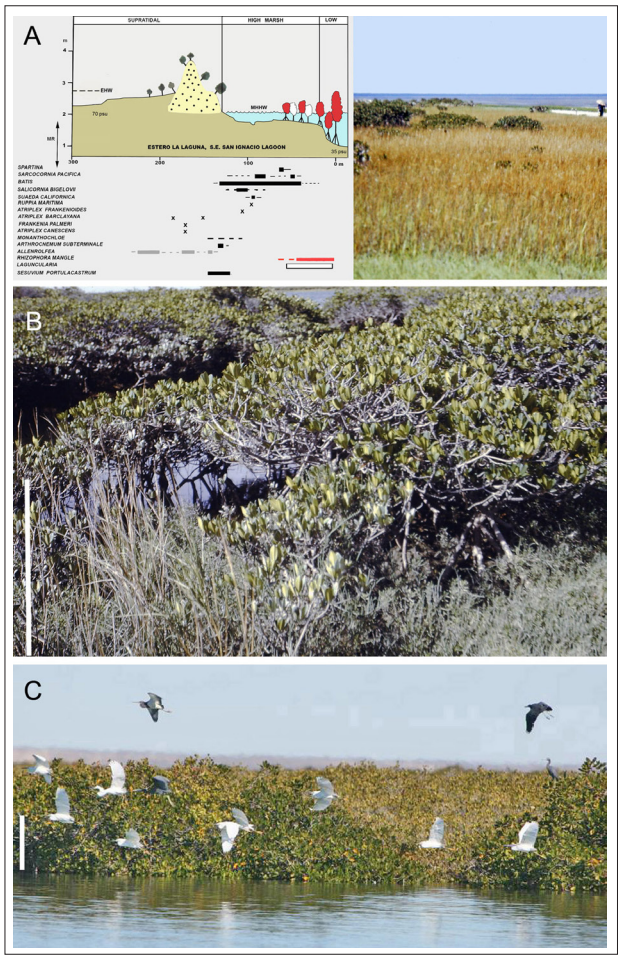


Figure 18 Estero del Coyote comparisons: aerial photographs in 1972 A and in 2017 (B, Google Earth), and images of taller vegetation than measured in 1971 at Campo René. C) Red mangroves in 2016 on the channel fringe where the pelican is c.1.3m high (from Mali Mish, with permission) and D) white mangrove in the middle marsh, November 2013 (from I.C. Feller) [67].

Aerial photographs for Estero del Coyoto in 1972 and 2014 show little evidence of change in the geoforms of the barrier lagoons or in distribution of wetland vegetation that comprised an estimated 7.1 km^2 of mangroves [51,67]. A 25% decrease of dead mangroves was reported by López-Medellín and Ezcurra for field work in 2007 – 2009 compared to a 2013 survey (I.C. Feller, unpublished images) when many shrubs had damaged leaves, propagules, and shoot-tips. In 1972, a year after the hurricane landfall at Pta Abreojos, there were many *R. mangle* seedlings in low marsh and germinating seedlings or yearling plants of *L. racemosa* in the upper low marsh; where most of the mature shrubs were c. 1 m high or shorter. Comparison of the 1972 aerial photography with a 2017 (Figure 18B) and 2020 Google Earth images shows only minor changes in topography but an increase in mangrove cover, suggesting recovery from the damage observed in 2013. However, the most conspicuous change is a 20% increase in mangrove canopy height. In 2013, red mangroves were up to 2.5 m tall (Figure 18C) compared to a maximum of 2 m in 1972; the white mangroves were also taller (>1 m) than in 1972.

For San Ignacio, the earliest account of mangrove ecology appears to be from Huey who noted that the mangrove shrubs were confined to the seaward areas of San Ignacio Lagoon (Outer and Lower Bays, Figure 5) where there was good tidewater exchange. He also found common *Spartina* grass, in contrast to Riosamena-Rodriguez and López Vivas who reported this as a recent adventive species at San Ignacio [69]. Near the high tide line there was saltmarsh with scattered areas of *Salicornia* interspersed with *Monanthochloe* (= *Distichlis littoralis*) where Marsh Sparrows nested. Huey's descriptions fit well with our observations in 1972 (Figures 5 and 19). Our transect data (Figure 19A) show that most of the red and white mangroves at Estero La Laguna were <1 m high, except in the lowest marsh zone where red mangroves were up to 2 m high. In the middle marsh, there were many shrubs with dead branches (Figure 19B) although the leaves and shoots appeared healthy. In 2014 – 2016, the mangrove canopy height on the south shore was >2 m and the cover was denser (Figure 19C). The areal extent in 2010 was c. 26 km^2 compared to 8.77 km^2 in c [51,53]. However, Cota-Lucero et al. reported very large mangrove shrub loss of 2,554 ha from 1990 – 2005, with an annual deforestation rate of 3.82% [70]. It is not clear why this estimate is so large, and Cota-Lucero noted that the difference could be due to inadequate ground-truth surveying and excluded of all salt marsh areas. However, they also considered that hurricanes and tropical storms could be source of severe damage, with 15 events being recorded in less than a decade from 1996 – 2004. For the entire region from La Bocana to El Dátil, López-Medellín et al. reported the loss of 65 ha from 1978 to 2005 but there was a net gain of 193 ha from 2005 to 2010 [64]. Riosmena-Rodriguez et al. (2009) describe changes in eelgrass and *Ruppia*, some of which may be related to hurricane impacts.

Figure 19 San Ignacio Lagoon comparisons. A) 1972 Transect data for Estero La Laguna, and B) image of short mangrove shrubs on the transect. C) dead branches of *Rhizophora* and *Laguncularia* in 1972. D) Dwarf *R. mangle* on South Shore of La Laguna; Egret wing-span is 1.3 – 1.7 m. Image of Mali Mish, with permission.



San Carlos-San Jorge area, Bahía Magdalena

In contrast to the minor commercial development of the northern lagoons in Climate Zone III, the Bahía Magdalena region has undergon relatively intense development since c. 1845 when American and other foreign ships hunted gray whales and harvested wood, fish, turtles, and oysters during the winter calving season [58,71].

In the 1930's, the Mexican government began to develop farming co-ops in the Magdalena Plain but the villages of Villa Insurgentes, Ciudad Constitución and the ports Puertos San Carlos, Aldopho López Mateos and Puerto Chale (Figure 6) remained small, with populations of <400 in 1960 and 1972. These small ports were mainly used for seasonal lobster and abalone fishing commissioned by Japanese financiers c.1912 – 1939, and for canning or drying produce for export [65]. In the 1980's, however, the Mexican government amalgamated the rancheros and ejidos into co-ops. By 1983, San Carlos was modern commercial port, exporting fish and produce from the surrounding agricultural fields where paved road spanned the tidal flats on bridges. A channel was dredged from the entrance of Boca de Soledad to Puerto San Carlos and Puerto Lopez Mateo that were developed to ship ranch produce from Villa Insurgentes. The US Navy used the bay in winter, v and maintained a customs office for ships that stopped for meat and produce supplies Dickey [58].

Today, industrial and artisanal fishing in the Magdalena-Almejas lagoon complex contributes about 55% of the total fish production in Baja California; whale- watching tourism is an additional source of income [59,68]. The resident population of the region expanded proportionally: In 2010, Ciudad Constitución (pop. 40,935), Ciudad Insurgentes (8,741) and Puerto San Carlos (5,538) were classified as urban areas, and Puerto Adolfo López Mateos had a population of 2,212. Only Puerto Chale remains a small village of 373 residents.

In 1972, Puerto Chale and San Carlos were small fishing camps, with roaming cattle that grazed on red and white mangroves in the high marsh (Figure 7D). Results of the 1972 transect studies (Figures 20 A,B) show that the fringe mangroves at both the Northern (San Jorge) and Central (San Carlos) sites in Bahía Magdalena were much taller (c. 4 m) than at San Ignacio and further north where canopy height was <2 m. At Bahía Magdalena, red mangrove dominated in the low marsh, with variable amounts of white mangrove, and relatively low amounts of black mangrove. At San Jorge (Figure 20B), in one of the flattest and least disturbed parts of the Bahía Magdalena region, there was a fairly rapid change in canopy height to 1 m or less with distance from the main channel and the soil salinity increased from 35 to 38‰.

In contrast to our 1972 study, a transect made by López-Medellín et al. near Boca de Santo Domingo a few kilometers south of our transect site shows that in 2009, there were notable differences in both mangrove composition and canopy height with distance from the channel (Figure 20B). López-Medellín et al. found that in 2009, the fringe mangrove was dominated by tall *R.mangle* (as we found at San Jorge) but the low marsh mudflat forest of *L. racemosa* and *R. mangle* was also taller and apparently lacked *A. germinans*. Inland, there was an abrupt decrease in canopy height and a replacement of *Rm* and *Lr* by *Ag*. An overall trend of mangrove reduction was noted for the lagoon fringe forest but the forest cover tended to increase landward in the high marsh where it mainly comprised small *A. germinans* shrubs. The *A.g.* shrubs were radiocarbon dated as younger than 1987 whereas the trees in the mixed forest were mostly 80mm – 135 years old. López-Medellín concluded that this pattern reflected a trend towards increasing rise in relative sea level (RSL) and a 2 mm increase in mean tidal levels since 1950, including large El Niño tidal anomalies in 1982 and 1997 when hurricanes Nora made landfall in BCS.

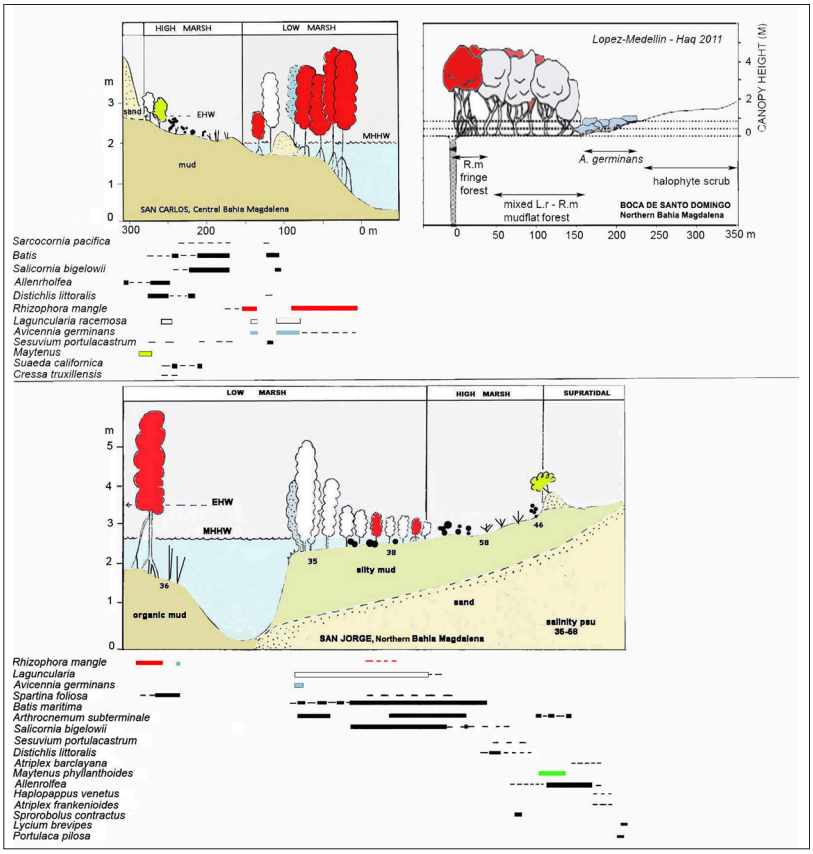
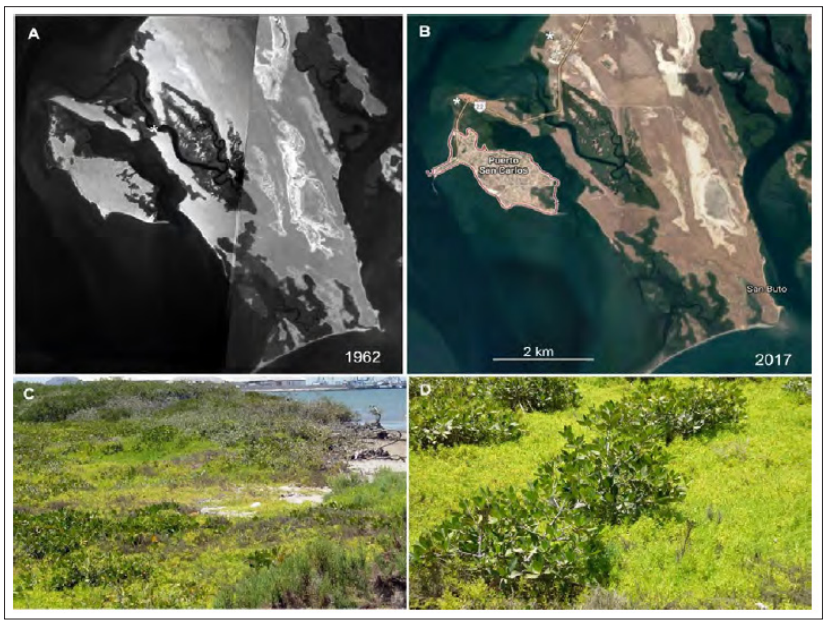


Figure 20 Transects of Bahía Magdalena tidal wetlands in 1972 at San Carlos (A) and at San Jorge (B), compared to a transect at Boca de Santa Domingo in 2009 (adapted from López-Medellín).

In 1972, before construction of a road to the islands of Puerto San Carlos, we made a transect on the mainland shore opposite the northern island (Figure 21A). The fringe mangroves were dominated by *Rm* 2 – 4 m high, with minor amounts of *Lr* and *Ag* (Fig. 21A), The transect crossed a low sand ridge, behind which there was shallow water with dwarf (1 m) red mangrove. Small (< 1 m) shrubs of *Lr* and *Mp* occurred in the upper high marsh.

Figure 21 Historical changes in the Puerto San Carlos area of Central Bahía Magdalena. A) 1962 aerial image from López-Medellín and Ezcurra and a 2017 Landsat Google Earth image (B) show the urban development of the port during the past 55 years. Asterisks mark locations of the 1972 transect (left) and sites with stunted mangrove vegetation (right) in May 2014. C) Small fringe mangroves in the marsh near the dockyard (in background) with many dead bushes, and stunted mangroves in depression. D) Close-up of stunted red mangroves in C).



In 2014, we examined the mangrove vegetation remaining in areas near the 1972 transect (Figure 24). Large differences in forest structure were found within Puerto San Carlos where diked roads (Figure 23B) now blocked tidal exchange between islands in areas that were mangrove- covered tidal flats in 1972. Near the dockyard, fringe mangroves were small (<2 m) and many were dead (Figure 21C). In the swale behind a low sandy beach ridge, the dwarf red mangroves were little higher than the *Batis* saltmarsh vegetation cover c.0.5 m (Figure 21D). North of the urban area, there was an extensive cover of mixed mangroves up to c. 2.5 m high, bordering eutrophic, saline ponds partly covered by *Enteromorpha* (Figure 22A). Here the fringe mangrove scrub was dominated by red and white mangroves of uniform height, as at Boca de San Domingo, with about 25% dead wood (Figure 22B). The upper edge of the saline pond was fringed by black mangrove shrubs up to 2 m high, behind which there was saltmarsh dominated by *Batis*, *Sarcocornia pacifica* and *Arthrocnemum subterminale*. Dwarf *R*. mangle saplings (Figure 22D) were present in the area landward of the black mangroves. The presence of tiny (10 cm, Figure 22C)) propagules on these small mangroves indicate that they were at least five years old (Hill, 2001). In 2014, there were also a few small black mangrove saplings in the high salt marsh at Pto. San Carlos, as reported for Boca de San Domingo by López-Medellín et al.

Figure 22 Mangroves at Puerto San Carlos in May 2014. A) Mixed mangrove shrubs (background) bordering a eutrophic saline pond, with black mangrove shrubs along the inland border. B) Close up showing large amount of dead wood in the mixed shrub forest. C and D) Stunted red mangrove in salt marsh at the upper edge of the wetland (D), with a very small propagule (C). Scale=20 cm

Overall it is difficult to estimate the long-term change in mangrove cover for the Bahía Magdalena-Almejas lagoon complex because of different methods used to determine the areal extent from aerial or satellite images. Estimates vary from a cover of 3,368 ha in 1990 that dropped to 814 ha (loss of 2,554 ha) within 15 years to a smaller loss of 1,500 ha for the same time interval from 1990 – 2005 [60,70]. The latter study also reported that only the shrub mangrove was highly disturbed, and that the monospecific fringe forest displayed a 48% increase. González-Zamorano et al. estimated a total mangrove cover of 23,600 ha. A fourth estimate López-Medellín concluded that from 1986 to 2001, there was an overall increase of 4,649 ha from 21,081 to 25,730 ha, with loss in the fringe mangrove and gains in the landward spread of black mangrove shrub, as determined by Landsat images. In 2004, López-Medellín and Ezcurra reported 20 – 50% increases in dead wood at Puertos San Carlos and López Mateo, respectively, but there was a 25% decrease the amount of dead wood at Puerto Chale. Despite these differences in measurement of changes in mangrove cover, however, there is a general agreement that this is one of the least impacted large mangrove areas in all of Mexico.

Gulf Coast

The Gulf Coast of Baja California was mapped and settled by missionaries much earlier than the Pacific Coast [58,72]. This coast and the adjacent Sierra de la Giganta range were also more densely populated by indigenous people, with an estimated 40,000 to 50,000 Indians in 1690. Settlement density probably ranged from a minimum in the hotter, drier climate Zone VI at the limit of mangrove distribution to more densely populated areas around the river mouths in Zone V, with maximum numbers in the higher rainfall Zone IV. Regardless of variations, the indigenous population at its height was never more than 150,000. In contrast, today the entire Gulf Region is called the "World's Aquarium" and it receives around 2.1 million tourists every year, mostly (c. 78%) USA and Canadian foreigners who contributed 7.8% of Mexico's GNP in 2006 [73]. Because of the longer history of land use and high population pressure on the unique marine fauna since 1978, several Gulf region mangrove sites were designated as protected areas: Islas del Golfo de California, Loreto National Marine Park, and Bahía de los Ángeles and Bahía de Concepción [49]. There is also a Ramsar conservation site at Punta Balandra.

Bahía de los Ángeles and Las Animas

Bahía de los Ángeles (B. L. A.) is the northernmost mangrove site in Baja California (mangroves on Isla Smith, a.k.a Isla Coronado, at 29.03 ^{o}N, -113.50 ^{o}W) and is the key area for predicting northward expansion associated with global warming. Bahía de los Ángeles is a deepwater, island-sheltered bay discovered in 1539 and first called Bahía de Lobos because of the many sea- lions. The present village of Bahía de los Ángeles on the NW shore was first visited by the Jesuit missionary Padre Juan de Ugarte in the 1720`s who noted a large rancheria of Cochimi Indians living onshore near a large spring, eating primarily shellfish from tidepools and mudflats [58].

However, it was another 40 years before the bay was colonised by missionaries and named Bahía de los Ángeles. A loading dock was built to provide a port for Mission San Borja (1762 – 1818) located c. 75 km inland. From 1899 to 1911, the Americans mined silver at Los Flores 16 km south of the bay, and they built a railroad and another dock on the bay shore. After the 1911 Mexican War, however, the mine was abandoned and the bay remained an obscure village that Steinbeck described in 1940 as having very large tides [up to 3.4 m], a tiny airfield, many vacant houses, and "*a few new buildings occupied by American fishermen or gun runners*" [31]. It remained this way until after 1945 when sport-fishing began to flourish, the dock and airport were reconstructed for tourists, and green turtles were harvested to near extinction to serve hotel guests. By 1960 and in 1973, however, B.L.A. has reverted to a fishing village and it remains small although linked to the Highway by a paved road in 1974. In 2010, the village had a population of c. 800, based primarily on sport-fishing, and tourism after the collapse of its commercial fishery because of overfishing [30]. In 2007, concern over degradation of the unique regional ecology of the region led to the inclusion of the bay in a joint government-NGO marine preserve, the Bahía de los Ángeles Biosphere Reserve.

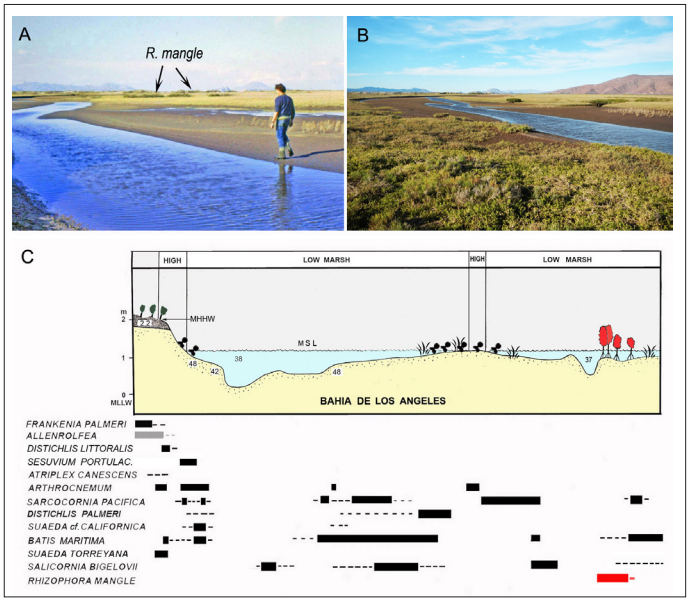


Figure 23 Bahía de los Angeles transect and comparison 1973 – 2013. A) John Rutherford at the La Mona transect 1 area in 1973, showing the sparse amount of stunted red mangrove scrub. B) Essentially the same La Mona area in 2013 (courtesy of I.C. Feller). C) Transect showing small amount of stunted red mangrove along the main channel and scattered areas of saltmarsh vegetation.

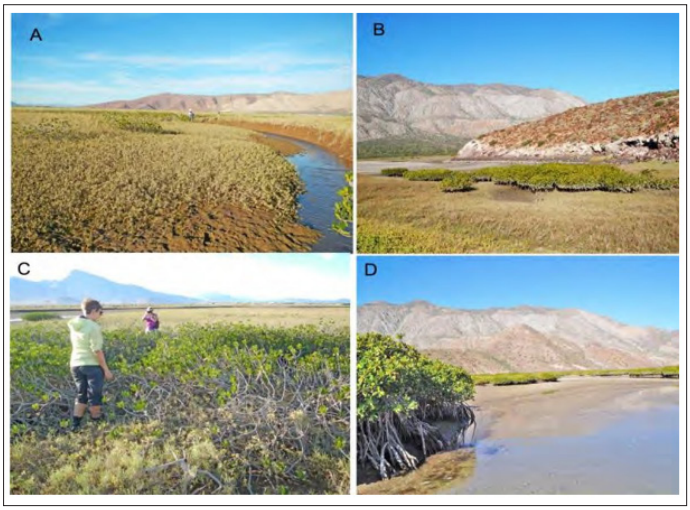
In 1973, a transect was made of the mangroves and salt marsh at estero La Mona in the southern bay (Figure 23C). Stunted *Rhizophora mangle* <1 m high was restricted to a few scattered patches of up to 40 bushes along the main channel behind the beach barrier where the water salinity was 37‰ (Figure 23A). In 1973, the mangroves did not grow on the inner sandy mudflats where the water salinity was 38‰ and soil salinity was 42 – 48‰ for the innermost channels.

The associated succulent and graminoid salt marsh species were similar to those seen by Johnston who visited Gonzaga Bay, B.L.A and Bahía Las Animas in 1921 [33].

Johnston described the regional halophytic ecosystems as having a littoral area dominated by red mangroves, with extensive tide-flats, saltmarshes and salt flats covered by mainly by *S. pacifica* associated with *Monanthochloe* (=*Distichlis littoralis*), *Batis maritima, Salicornia europea* (now *S. bigelowii*), *Frankenia grandiflora* and *Suaeda ramossima*. Thickets of *Allenrolfea occidentalis* and *Frankenia palmeri* occupied sandy areas of the upper littoral margin. However, Johnston did not record *Rhizophora mangle* for either Gonzaga Bay or Bahía de los Angeles. In fact, he described the northernmost mainland occurrence of this species in 1921 as "*a single puny bush at about 28º 50'N*" on the shore of Bahía Las Animas (c. 10 km east of La Mona). In 1973, we found that mangroves were common at La Mona, with associated grasses *Distichlis palmeri* and *D. littoralis*, and *two Suaeda* spp. (Figure 23C) or morphotypes of *Suaeda nigra* (Rafinesque) J. F. Macbride. A conspicuous feature of the La Mona mangroves in 1973 was the large amount of dry plant litter resembling *Zostera* that was trapped by the stems (Figure 10A). Unfortunately the exact source of this litter was not determined, and today B.L.A. is beyond the northern growth limit of *Zostera* in the Gulf of California where it is replaced by red algae *Gracilaria* and *Gracilariopsis*.

In November 2013, a survey at La Mona led by I.C. Feller of the Smithsonian Environmental Research Center showed little difference in the canopy height or cover of mangroves and marsh composition in the outer channel area (Figure 23B). The areal cover in c. 2006 was estimated as 27.41 ha compared to c. 250 m^2 at Bahía de Las Animas (Figure 24 B, D) [27]. In 2008 and 2013, the canopy height of mangroves appears to have been >1 m on mudflats flanking more sheltered areas of the tidal creek heads (Figure 10C, 23C) and these larger shrubs were not partly buried in plant debris. Some taller mangroves, however, had a lot of dead wood. In contrast, at southern Bahía Las Animas (c. 28.80 ºN, -113.34 ºW), images taken in February 2017 show that the mangroves (mostly *R. mangle*) were >1 m high, with a more continuous cover and little dead wood (Figure 24B, D). The present extent and density of the Las Animas mangroves is a stark contrast to the one puny red mangrove found by Johnston in 1921.

Figure 24 Comparison of red mangroves at Bahía de los Angeles in November 2013 (left) and Las Animas in February 2017 (right). A) Sparse mangroves border steep-sided upstream tidal channel, B) salt encrusted red mangrove up to 1.5 m, at low tide, Las Animas. C) dead wood of larger mangroves at Los Angeles. D) Taller, denser red mangroves at Las Animas.



There is no clear reason for the difference in mangrove cover and density at Bahía de los Angeles compared to Las Animas. Both areas are subject to periodically intensely hot mountain winds that blow offshore at speeds of up to 90 km hr^{-1} and a daily maximum of up to 49°C was recorded at Bahía de los Angeles in 1997 compared to the minimum of 1°C recorded for January 2002 [74]. These extremes and the greater wind fetch in the semi-enclosed, c. 15 km-long Los Angeles Bay may be less favourable for mangrove gowth than the Las Animas estuary which is further from the Sierra de San Borjas hot winds, and which receives intermittent river flow. However, climate and salinity data for Las Animas are needed for precise comparison.

Mulejé

In the arid Central Gulf Desert Zone V, Estero Mulejé is a 3 km-long tidal estuary at the mouth of Rio Sta Rosalia de Mulejé, one of two large rivers with year-round flow in this phytogeographic zone. Presence of water explains its millennia-long use by indigenous people and its early settlement (1705 – 1828) by missionaries [58]. The missionaries cleared large areas for farming of European and tropical fruits, tropical vegetables, and date palms that now fringe much of the shoreline. A stone dam was built to irrigate this farmland. The original regional Indian population of about 2,000 dropped to less than 100 by 1782 [55]. In 1770, the agricultural area was destroyed by a massive flood but it was resettled in 1776. After the missions collapsed in 1828, settlers from the Mexican mainland comprised most of the population which rose from c. 950 farmers and fishermen in 1960 to 1973 to c. 3,820 at present.

Mulejé was a battlefield during the Mexican-American War when it was occupied by the Americans for one day on October 2, 1847 and renamed Heroica Mulejé for the Mexican victory. A painting by the field artist William H. Myers at the Battle of Mulejé shows a large amount of cleared land on the shore of a wide estuary that was navigable to large sailing ships in 1847 (Figure 25A). A 1908 photograph (Figure 28 inset) shows that salt was harvested from a pond on a tree-cleared sand barrier at the mouth of the estuary but there was no lighthouse, implying that the main channel was deep and navigable. In 1921, Johnston collected *L. racemosa* shrubs 2.4 to 4.5 m high at Mulejé. In 1940, Steinbeck noted mangroves there and at San Lucas [31]. By 1956, however, Mulejé estuary was largely filled by mangrove-covered mudflats, the entrance was partially closed by a sandspit, and a lighthouse was built on the north shore for safe navigation (Figure 26A). About 30 years later, the estuary was described as a brackish lagoon only navigable by small boats and extensive mudflats filled large areas on the south side (Figure 25B) [42].

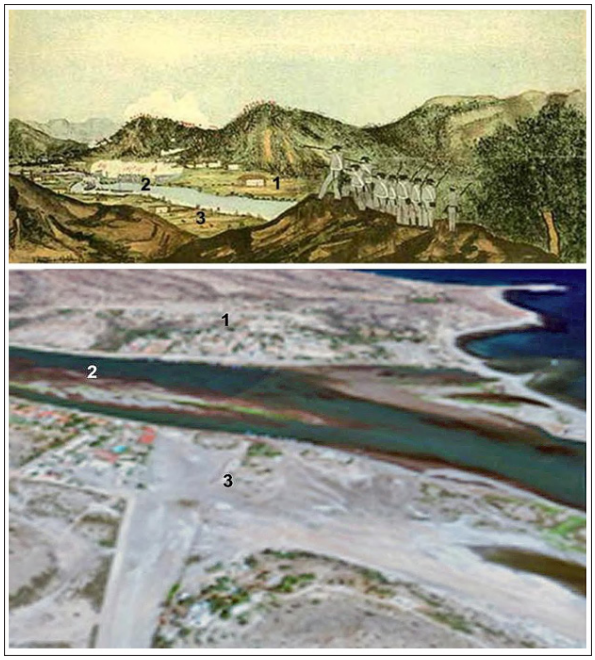
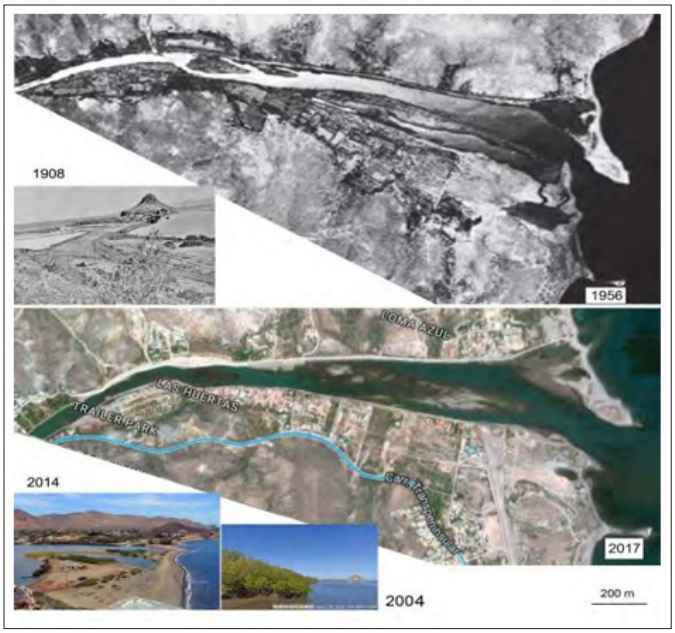


Figure 25 Mulejé estuary from a hill south of the estuary mouth in 1847 (A) and in 2017 as seen from the same hill, on a Google Earth Landsat image (B). The numbers mark notable differences: 1) the urban area of Mulejé now replaces open fields; 2) the area of small mudflats now extends far eastward to the hill; 3) the south shore farmland is now developed as tourist resort area, with bare areas marking an airplane runway and recreation vehicle park.

Whitmore et al. reported that before 1974, both sides of the Mulejé estuary and many small mudbanks were covered by mangroves inland to the irrigation dam that was rebuilt with concrete to stop upstream intrusion of salt water. A 1956 aerial photograph shows that the mudflats and shoreline had a dense mangrove cover and there was a tidal channel fringed by mangroves behind the recurved spit near the entrance (Figure 28A) [75]. Our 1973 survey showed that the mudflats were colonised by small (c. 2 m) shrubs of *R. mangle* and *L. racemosa* which also lined the shore and covered the sandbar linking the north shore and lighthouse island. Major changes began with a surge in tourism after completion of the TransPeninsula Highway in 1974 and eradication of malaria by DDT spraying. The tourist development included removal of the south shore mangroves, backfilling to 1 m above mean high water for a recreation vehicle (RV) park, and construction of waterfront hotels and holiday homes accessed by wharves (Figure 15.7). In 2004, there was still some north shoreline with tall *R. mangle* (Figure 26B, inset) and in 2008, the south shore still had a tidal pond lined with small mangroves (Figure 2). Landsat images in 2017 show that the southern tidal channel was entirely filled in, with only a small, open pond remaining (Figure 26B). An estimated 6 ha of mangrove were removed after 1956, amounting to c. 20% of the 32 ha measured by Gonzáles-Zamorano et al. for the entire Mulejé + Concepción Bay region.

Figure 26 Mulejé comparisons 1956 to 2017. Top: 1956 aerial photograph from Bale and Minch showing dense mangrove vegetation on the lighthouse sandbar and along a tidal channel south of the estuary entrance. Inset is a 1908 image showing clearance of mangroves on the inner lighthouse sandbar for commercial salt-harvesting [75]. Bottom: Same area in February 2017, with insets showing reduced mangrove area on the lighthouse sandbar 2014 compared to 1956, and dense shrubs on the north bank before 2008 (inset image). Much of the south shore is now cleared of mangroves, and gravel flood protection berms now line both banks.



The Mulejé case history largely illustrates the direct impacts of anthropogenic effects on the mangrove ecosystem. However, another component of destruction includes sporadic mass

flooding of the river that drains 16 watersheds in the Sierra de la Giganta. A 1770 flood event destroyed the first mission but large

floods did not re-occur until 1914 and 1955. In 1967, Hurricane Olivia crossed the peninsula as a tropical storm, strengthened over the Sea of Cortez, and made a second landfall near Mulegé as a Category 3 hurricane that left 1500 people homeless and isolated the town for three days [76]. There were no more floods until 2006 when Hurricane Juan washed out the bridge and road to the lighthouse killing many mangroves [20,77]. This Category 4 storm was followed shortly by two other devastating floods: Julio in 2008, and Jimena in 2009. In 2007, the channel levees were constructed (Figure 27B) but the barrier intended to protect actually narrowed the river and caused more extensive flooding. By 2014, however, mangroves had recolonised the mudflat and part of the lighthouse sandbar (Figure 26 inset). In October 2014, Hurricane Odile again brought torrential rain and flooding to Mulejé but aerial photos during the flood and in 2017 (Figure 26) show that some mangroves remained in place.

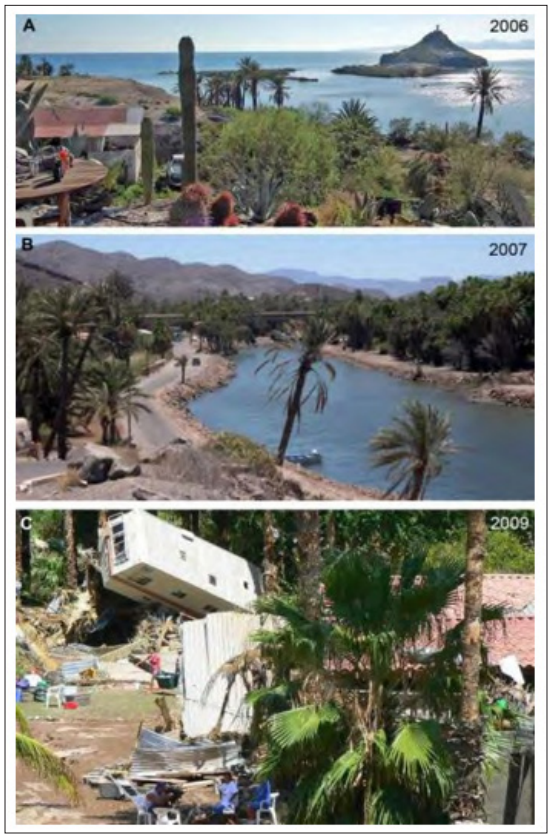


Figure 27 Flood damage at Muleje 2006 to 2009 (Anoymous, 2014). A. Flooded sandbar at the estuary mouth in 2006. B) wide gravel and sand levees in front of the Highway bridge built in 2007. C) Property damage after Hurricane Jimena in 2009, when large trailer homes were blown in to the trees; other vehicles and houses were blown into the water where their remains add to the sediment in-filling of the southern estuary.

Bahía Concepción

Most of the 40-km long Bahía Concepción bay shoreline is rocky and steep-sided, with few areas suitable for tidal wetland development. Mean tidal range (1.4 m) is lower than at Bahía de los Angeles and water salinity is 35.5‰, 2.5 psu lower than B.L.A. There are no sources of permanent freshwater, and the area was largely uninhabited in 1960 and 1973 except for a few ranches with goats and cattle, and a fishing camp at Playa Armenta [55]. Before the TransPeninsular Highway, the shore was largely inaccessible but mangroves were seen at Santispac, El Coyote, Playa El Requesón and Sta. Rosallita (Figure 28). A total mangrove area of 46 ha was estimated from 1978 and 2005 aerial images, which is slightly larger than the 32 ha estimate of Gonzaléz-Zamorano et al. made around 1995 [49].

Our 1973 field observations showed the presence of small red, white and black mangrove shrubs up to 2 m high, bordered by salt-marsh vegetation dominated by *Batis*, *Sarcornia*, and *Allenrolfia*. In contrast, Johnston reported R [33]. *mangle* over 9 m high at Coyote Bay, and <4.5 m-high L. racemosa at El Coyote and Playa Escondido; he did not mention the presence of *A. germinans*. In 1973, *R. mangle* tended to border the main tidal channels behind the sand bars of of the small beach barrier lagoons. Red mangrove was densely intermixed with *L. racemosa* in the low tidal marsh, while *A.germinans* dominated the drier, more saline upper marsh bordered by halophytic shrubs and succulent perennials. (Figure 28)

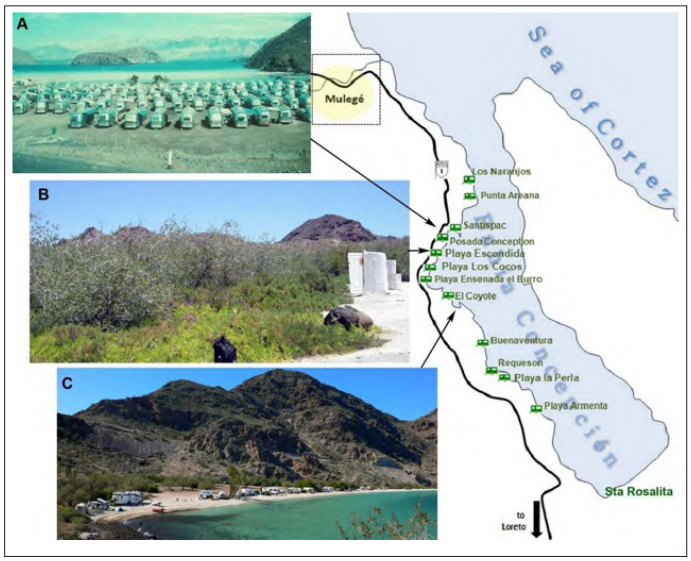
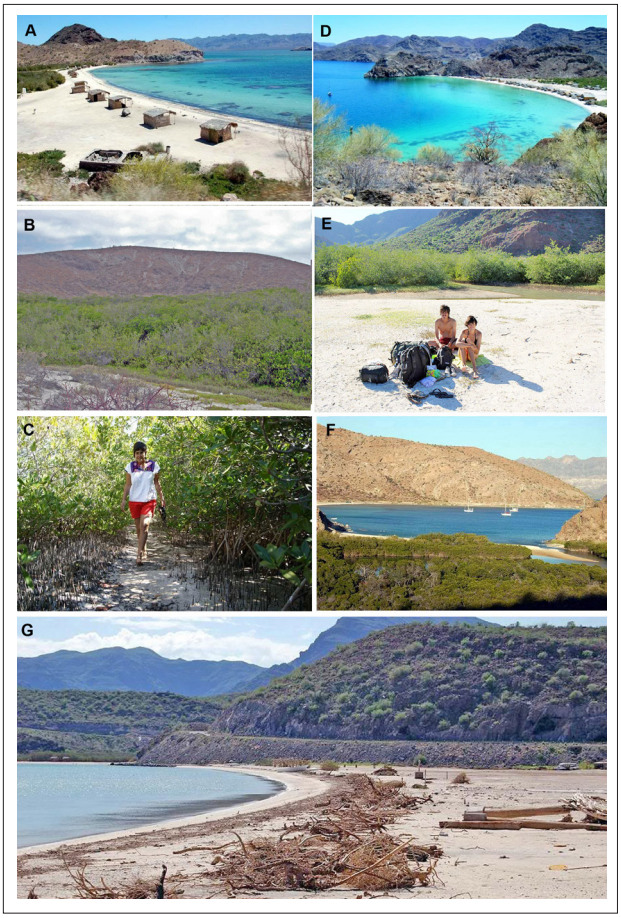


Figure 28 Bahía Concepción tourist map showing the 13 main campsites, with photo images for 1974 to 2014. A) 100 airbuses rallied at Posada Concepción in 1974 where all vegetation was cleared (Panoramio image). B) Playa Escondida in May 2014, with 3 m-high white latrines for campers provide a scale for mixed mangrove scrub. C) Campers at Playa El Coyote in January 2012, below the Highway cut into the mountainside.

CONABIO report a slight increase in mangrove cover from 2005 (46 ha) to 2012 (57 ha) and give the average canopy height as 1.6 to 2.3 m, which is consistent with our observations in 2014 (Figure 29B,C) (49]. The CONABIO document lists several problems that led to inclusion of the Bahía Concepción mangroves in a National Protected Area PN02. The salient factors are deforestation for road construction and tourist facilities (Figure 29), and damage by tourists who also use mangrove cover for latrines and waste disposal. Hurricane damage in this sheltered bay with no major rivers appears to be minimal: mostly excess large driftwood, including tree-trunks, on the beaches. Despite the anthropogenic impacts, the areal extent and height of mangroves in the coves of this sheltered bay appear have to increased since 1973.

Figure 29 Bahía Concepción: impacts of road construction and tourism. A and B) Playa Escondida with ramadas and latrine by the mangroves at height of tourism in January 2010 (A, Magicplaces image) and (B) on the inland fringe of the mixed forest in late season, May 2014. C) Mixed white and black mangrove forest at El Requesón, 2010. (Viajero Sustenable image) (D and E)

Ensenada el Burro in 2010 where there are houses constructed over campers (D) and a narrow tidal channel with black mangroves and scattered white mangroves (E) in 2010. F) Red mangroves mixed with large *L. racemosa* in Playa Santispac, 2010. G) Santispac beach after Hurricane Jimena, 2009 [77]. Note the TransPeninsula highway carved into the rocky hillside in 1976 using dynamite and bulldozers.



Loreto Area

The Loreto area includes the city of Loreto (population 25,300 in 2014; 10,010 in 2022) and several small coves with mangroves located north and south of the city. The entire area from San Juan de Bautista Londó (a.k.a. San Bruno) at 26.22 °N, -111.39 °W in the north to Puerto Escondido and Liguí at 26.74 °N, -111.26°W are now protected within the Bahía de Loreto National Park. Protection was needed because of intense pressures from tourist and sport-fishing developments after 1960 and 1973 when Loreto's population was only 1,600 [55]. Located towards the south end of Zone V, the temperate winter climate, large airport, and the availability of freshwater from the Arroyo Las Passas and a thermal spring at San Juan rapidly made Loreto a favourite tourist destination for American visitors after completion of the TransPeninsula Highway in 1976. Furthermore, in 1973 the Mexican government organisation FONATUR (*Fondo Nacional de Fomento Al Turismo*) identified Loreto as having high tourism potential, and c. 30 km^2 of land was purchased for development in the Nópolo and Puerto Escondido-Liguí areas [78]. By 2013, the tourist population was 60,000; it continues to increase as more hotels, holiday villas, and golf courses are built [79].

Loreto was the first Spanish settlement in Baja California. In 1697, Juan de Salvatierra landed in Bahía Concepción but he chose to settled further south on the Las Parras river delta (Figure 29) where there was freshwater. He found a large Indian population based on farming and fishing in the area called Conchó because of its red mangrove trees. De Salvatierra wrote that during the construction of the mission he employed three lumberjacks and "*lived on the beach under an enramada made of the mangrove*" [80]. De Salvatierra was of Italian origin and he renamed the Conchó mission "Our Lady of Loreto de Conchó"to honour an Italian Saint. This mission was built on a fan-lobe delta and it supported 70 colonists by 1704 [58].

However, agricultural land with water was sparse, so the settlement was extended north along the coast to a thermal spring at San Juan de Bautista Londó and south to Liguí where there is another large outwash fan with fresh water. After expulsion of the Jesuits from Baja California in 1767, the Franciscans focused on northward expansion to Alta California. Hence the population decreased between after 1768, aided further by smallpox, locust infestations and prolonged droughts [58]. However, Loreto remained the main town for 150 yrs and was the capital of Baja California until 1829 when it was largely destroyed by a hurricane, damaged by an eathquake in 1977, and reverted to a fishing village. The mission was fully restored in 1948 and the city slowly revived after the 1950's when sport-fishing began to trigger the tourist boom.

Figure 30 Arroyo de las Parras channel of the delta complex at Loreto. A) August 28, 2014, before Hurricane Juliette, showing bar mouth features downstream of harbor developments, and mangroves on mudflats in the Arroyo. B) February 2017, after construction of channel levees following hurricanes Juliette, Odile and Newton in 2014 and 2016, showing erosion of the mudflats and tributary channel sand-bars, and extensive urban development south of the Arroyo.

Loreto is located on a fan-lobe delta complex, with the largest channel Arroyo de las Parras (a.k.a. San Telmo) crossing its center north of the Colonia Zaragosa residential development (Figure 30) [81]. In 1973, most of Loreto was urbanised, with only a thin fringe of mixed mangrove scrub on the shores of the estuary. At Nopoló inlet 14 km to the south, however, there was a large area (ca. 20 ha) of channels fringed by tall *Rm* with *Lr* grading inland to *Avicennia* shrubs and a border of salt-marsh with *Batis* and *Sarcocornia subterminalis*. By May 2014, however, there were no mangroves in the outer Las Parras estuary east of the highway (Figure 32) and there only ca. 1.25 ha of mangrove scrub remained within the golf-course constructed at Nopoló (Figure 33).

These 1973 – 2014 changes can be attributed to two main factors: 1) river flooding at Loreto and 2) development of "sustainable" tourist industry at Nopoló. The flooding in Loreto differs from that at Mulejé (Sect. 5.1.2) where the river has a large drainage basin that disperses some flood water and eroded sediment, thereby reducing flood impacts in the estuary. In contrast, the drainage basins feeding the channels of the Loreto fan delta are small, resulting in very rapid responses to climate and tectonic changes and larger impacts at the river mouths. Regionally, the highest river erosion rates are in the arroyos of the Las Parras and El Tular drainage basins flanking the Colonia Zaragosa housing development. The Loreto delta front is also exposed to wave and current erosion; hence, a protective harbour wall, breakwaters and shoreline rock embankment were built. These structures resulted in the downstream accretion of sand bars in a protruding birdsfoot-type distributary channel at the mouth of Arroyo de las Parras (Figure 31A).

Figure 31 Loreto Arroyo de las Parras flood impacts. A – C May 2014, after Tropical Storm Octave in October 2013, showing the new levee built east of Nicholas Bravo road and mud in the estuary at low tide (A), view across the estuary to Zaragosa at high tide, with Sierra de la Giganta in background (B), and remnant flood debris on the beach (C). D) Highway washout during Tropical Storm Octave. E) Zaragosa after Hurricane Odile in September 2014. F) Highway flood during Hurricane Newton, 2016.

During large floods, the distributary levees are eroded (Figures 30, 31C) and sandy mud is deposited directly in the river channel. Large floods are not new in Loreto but the records for 1970 to 2008 (Navarro-Lozano, 2009) shows that from 1983, larger storms occurred, depositing >500 mm of rain per day. Also, starting in 1992, the flood frequency increased from decadal- scale to 2 – 5-yr return intervals. The floods cause extensive damage to roads, property and infra- structure in Loreto (Figure 33D – E) and drinking water was polluted. Therefore, after Tropical Storm Octave in October 2013, rock and mud levees were constructed in the Las Parras estuary below the highway bridge (Figure 31A – C). In May 2014, we learned from the resident naturalists that most of the mangroves had been washed away and there were only a few, very small shrubs on the Zaragosa shore (Figure 31B). The Loreto case history provides an example of scrub mangrove destruction resulting from urban encroachment in an arid coastal region and increasing frequency of El Niños and tropical storms that has been associated with ocean warming [23,24]

In contrast to the sustained history of mangrove harvesting and flood-driven changes at Loreto, the case history for Nopoló is an example of an effort to restore mangrove habitat. In May 2014, a small remnant grove of mangroves was present above the TransPacific highway bridge across an arroyo that formerly drained into the protected cove of Nopoló estuary located behind a barrier beach (Figure 32A). The 1970's Baja California FONATUR development of Nopoló began with a hotel and golf course but failed to attract buyers for holiday housing [82]. In 2004, it was re-invented by the Loreto Bay Company to avoid high-rise hotels and to capitalize on the demand for second homes from baby-boomer Americans and Canadians. More than 6,000 luxury beach houses were built in clusters of villages (Figure 32E). Water was supplied by strict conservation and recycling, watershed restoration and desalination. Recycled wastewater from Loreto was used to water the golf-course that was replanted with salt-tolerant paspalum grass. In a partnership with the Loreto Bay Foundation, a program of ecotourist sustainability and estuary restoration was begun by digging 8 km of tidal canals and restoring the mangrove wetlands by planting thousands of mangroves from a nursery on the channel shore (Figure 32D) [83]. The red mangrove grew more slowly than white and black mangroves but survival rate (70 – 95%) of all transplants was high. The mangroves cover an area of 7.8 ha [49].

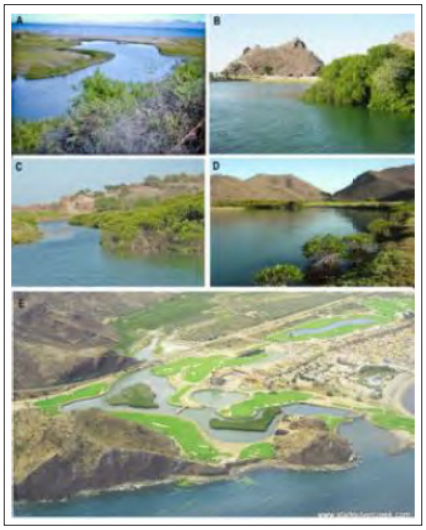


Figure 32 Nopoló sustainable tourist development. A) Remnant pond with small mangroves and saltmarsh behind the beach barrier in 2003. B) Entrance to artificial tidal channel in 2014. C) Island of mixed red and white mangroves and channel fringe with black mangrove shrubs, 2014. D) Main channel 2014, with transplanted mangrove seedlings on the shoreline. E) Aerial view of tidal channel, golf course and pond and mangrove islands (from Stark Insider, with permission).

Overall, it is difficult to evaluate the net change in mangrove area in the Loreto-Nopoló region. The missionary records clearly indicate that the landmark large trees were cut for timber. Johnston found red and white mangroves at Loreto, Pto. Escondido, Juncalito, some up to 7 m high in 1921. However, Steinbeck (1951) makes no mention of mangroves at Loreto in March 1940, although he comments on the abundance of mangroves at Puerto Escondido (Piedra de la Marina point) where the hot air was filled with scent of black mangrove flowers [33]. Google Earth images show that by 2009, the vegetation in the inner harbour of Pto. Escondido is mostly replaced by marina facilities, and only a small area (c. 0.1 ha) of red and white mangrove scrub rening in the harbor. One solitary *L. racemosa* tree survived at Juncalito in 2014. Aburto-

Oropeza et al. gives a mangrove area of 80 ha for Loreto in 2008; however, González-Zamorano et al. have a much lower estimate of 3.34 ha for 1993 − 2006 between Pto. Escondido and Loreto.

Discussion: Scrub Mangrove Forest Hazards, Vulnerability and Management

Hazards

In the 1972/73 survey of Baja California mangroves, the only obvious hazards to the mangrove scrub woodland were minor grazing by cattle in the Bahía Magdalena-Almejas area, and loss of black mangroves west of La Paz in cleared areas and where tidal exchange was blocked by during road construction [13]. The scarcity of mangroves at Santa Tomas and Cabo San Lucas may have reflected early destruction in the few areas suitable for wetland growth on these shores but there are no early records of mangrove collections except *Conocarpus* that would indicate large amounts of the shrubs before the post-1974 urbanisation. By 2008, however, Baja California mangroves were described as an endangered ecosystem, with human encroachment being considered the primary hazard despite government efforts to establish protected areas. Extensive changes in and around La Paz have been documented by Holguin et al. and Mendoza-Salgado et al. [19,20].

To evaluate the main hazards to survival of the arid region scrub mangroves, we first examine the magnitude of changes in areal extent reported for Baja California. The earliest report is for 1973 to 1981 in La Paz Bay when there was a measured 21.4% loss in mangrove extent from 207 to 162.8 ha because of industrial and tourist developments [19]. In 1994, the mangrove extent for the whole peninsula was estimated as 12,120 ha, with the largest losses reported for La Paz and Mulejé due to human impact [48]. In contrast, estimates based on aerial and satellite images recorded much larger mangrove extents: 23,952 ha for 1986, with an increase to 31,527 ha by 2001 [84]. These data and an estimate of 21,848 ha for the Bahía Magdalena-Almejas complex alone, suggested that the mangrove vegetation was thriving in Baja California, mainly from the inland expansion of black mangroves in southwest Magdalena Bay [12]. Giri et al. reported a total of 741,917 ha for the whole of Mexico as determined from Landsat data for 1997 – 2000. However, their map shows mangroves north of Viscaino Peninsula where there is only saltmarsh; therefore it appears that the Giri baseline estimate is too high. This error points to the difficulty of determining acreage of arid region dwarf mangroves from satellite data, as also reported by Alatorre et al. (2011) for Sonoran dwarf mangroves.

Using a more sensitive, verified classification of Landsat imagery, Cota-Lucero et al. measured a loss of 2,454 ha with an annual deforestation rate of 3.83% for San Ignacio Lagoon from 1990 to 2005, and a smaller loss of 854 ha (0.33% per year) for the Bahía Magdalena- Almejas Lagoon Complex [70]. They concluded that the losses were primarily related to hurricane and drought events, and they advocated improved monitoring at the limits of mangrove growth. López-Medellin and Escurra also reported large numbers of dead mangroves near Pta Lopez-Mateo as possibly being related to discharge of hot water from canneries [67].

This variability in areal estimates makes it difficult to assess the primary hazard to survival of the mangroves at the limits of their distribution in the Northern Hemisphere. On the Gulf Coast of Baja California north of La Paz, human encroachment after the TransPeninsula highway completion in 1974 seems to account for most of the changes in woodland extent between 1972/3 and 2011 – 2017. Highway construction, coupled with the post-World War II recovery of the American economy, triggered a boom in tourism that was matched by a population expansion (Figure 32A) based on this industry and its associated infrastructure (hotels, housing, airfields and access roads).

Our case histories show that anthropogenic changes in the Baja California mangrove woodland north of La Paz and San Carlos, Bahía Magdalena actually began in the 18th C with the establishment of Spanish missions on the Gulf Coast. The first European settlers used mangroves at Loreto for timber, and at Mulejé, riparian fringe mangroves were cleared for farming of non- native fruits, e.g. date palms and citrus. However, the early 20th C reports of mangroves up to 7 m high show that isolated Gulf Coast areas escaped cutting [33]. In contrast, today, few such trees remain: one near La Aquililla, and others at scattered sites around Loreto and La Paz. Missions were not established on the Pacific Coast, and there is no evidence of wetland changes there before the short-lived whaling era from c. 1845 – 1869 when wood was harvested at Bahía Magdalena [58]. Despite the 1930's start of large- scale agricultural development and war-time exercises in Bahía Magdalena, the ports remained small until the 1980's urban developments. The Pacific Coast south of Viscaino Peninsula also remained less accessible by road after the building of the TransPeninsula highway. In contrast, the government promoted road development for ecotourism on the Gulf Coast. Here shrub mangroves have largely survived in isolated coves lacking easy road access. In Bahía Concepción, these pockets are now being reached by campers using crude dirt roads, with associated slope erosion and in places, eutrophication from latrine usage. López-Medillín and Ezcurra warn that recent accelerated population growth and increasing construction for tourism and industry may seriously threaten these remnant mangroves in the future [67].

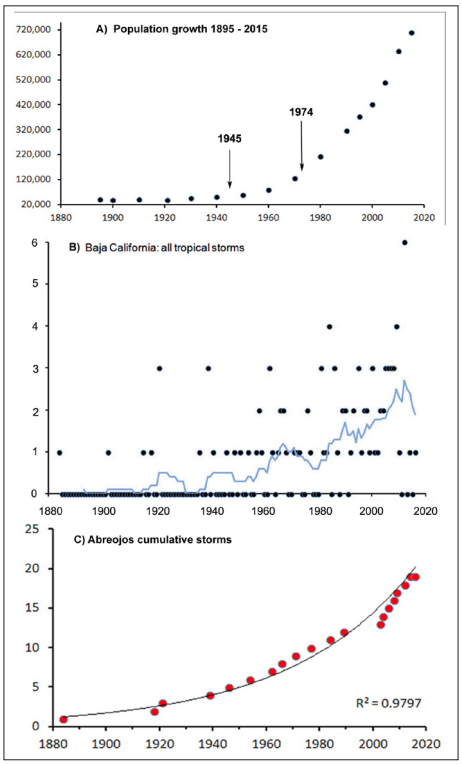


Figure 33 Population growth versus climate change in Baja California, from INEGI census records. A). Growth of resident BCS population from c. 1900 to 2015 (excluding seasonal tourists).

Arrows mark the start of tourism in 1945 and TransPeninsula Highway completion in 1974. B) 10-point running average shows gradual to rapid increase in number of tropical storms per year since 1880. C) Cumulative storms at Punta Abreojos 1880 to 2017.

Although population pressure may be a major hazard contributing to recent changes in the areal extent of the scrub mangroves, there is also evidence for direct and indirect impacts of climate change since the 1940's. In this arid region, the high winds, flooding and erosion that accompany hurricanes are also a significant hazard. The mission records from 1697 to 1828 show that hurricane-generated large-scale flooding of the estuaries at Mulejé and Loreto was severe but infrequent (c. 50 year recurrence) on the Gulf Coast. However, records for Baja California from 1880 to 2016 (Figure 33B) show an increase in hurricane frequency from c. 1940 to 1977, followed by a steep rise in cumulative frequency after 1986. Climate and tree-ring records also show that from 1860 to 1996, there were intervals of prolonged droughts (10 to 20 years) from 1939 − 1958 and from 1967 − 1976, in addition to shorter (1-2 yr) decadal-scale dry years [85]. The droughts coincided with La Niña cold intervals. Since 1983, however, droughts have been less frequent and less severe as a consequence of the increased frequency of storm rainfall events.

Photo-records for Mulejé indicate that the Baja fringe mangroves survived the flood hazards in 1914, 1955 and 1967 but their extent was greatly diminished after construction of levees in response to the increased storm frequency from 2006 to 2008. Levee construction at Loreto in 2014 also seems to have led to virtual elimination of the estuarine mangroves. In contrast, the areal extent of shrub mangroves has increased in some sheltered Gulf Coast cove populations. In these protected beach-barrier settings without river influence, mangrove extent and canopy height have increased since 1973 as shown by field observations in 2014, and by aerial surveys for the interval 1978 – 2005 [49]. These changes suggest that in non-estuarine locations, the increased precipitation has compensated for any shrub woodland losses due to storm damage.

On the Pacific Coast, at the northern limit of mangrove growth in the barrier lagoons at Abreojos and El Coyote, there is no river drainage but there is greater wind exposure than on most of the Gulf Coast. Here mangrove height has also increased since 1972 when piles of *Zostera* litter and stunted mangroves indicated recent storm damage, possibly combined with the effects of drought since 1967. Historical storm records for this area (Figure 33C) show that there has been a significant ($R^2 = 0.98$) increase in storm frequency since 1880, with the exponential curve steepening around 1970. In the Bahía Magdalena area, López-Medellín et al. attributed the expansion of high marsh (backwater) black mangroves to warming climate and increased frequencies of El Niño's during the 1980's − 1990's, with a corresponding erosion of the red mangroves on the storm-exposed seaward margin [84]. López-Medellín et al. (2011) reported that monthly averaged sea-level values for the Pacific coast from La Jolla to Los Cabos show a general rise in sea-level relative to 1950 that is correlated with a Multivariate ENSO (El Niño Southern Oscillation) Index. They noted extreme tidal anomalies (+20 cm) for the El Niño years 1982 and 1997 that would have flooded large areas of the coastal salt flats in the Viscaíno Zone III. They attributed the change in mangrove extent to a total c. 80 mm increase in sea-level since 1950, coupled with a linear increase in El Niño intensity. They consider that the benefits of the inland mangrove expansion doubtfully offset the coastal erosion hazards.

Vulnerability

Cintrón-Molero and Schaeffer-Novelli commented that like most pioneer species, mangroves generally have a high resilience and capacity to recover from environmental disturbance, but species may be more fragile near their limits of tolerance [37]. They considered that geomorphology (spatial availability, sediment supply and wave energy) is a primary factor for survival and that vulnerability varies with structural classification. Riverine forest requires low salinity and high nutrients, fringe forest needs shoreline protection, and basin forest requires periodic seawater flooding. Our 1972/73 data on relationship between diversity and geoform (Figure 13) are not based on mangroves alone but they point to a general decline in wetland diversity with increased aridity for all tidal zones: high, low and intertidal floras. This negative trend is steeper for hypersaline estuaries where the tidal channel entrance is periodically blocked sand in low rainfall years. The blockage results in increased salinity in hot, arid regions where evaporation is high. Recent increases in salinity in the mud-filled Mulejé estuary and the channel closure at San Gregorio, at the mouth of the once-navigable La Purisima River, may account for low diversity and small mangrove extent at these estuarine sites.

Our field data for soil water salinity (Figure 14) also highlights the relatively limited range of salinity tolerance (0 – 45‰) for the four main Baja California mangrove species compared to the the low marsh herbs (20 – 60‰) and wide-ranging succulents *Batis maritima and shrubs Arthrocnemum* and *Allenrolfea* (up to 90 and 250‰, respectively). *Conocarpus erectus* was not found where the salinity was >2‰ although at Fort Myers, Florida, where annual rainfall is 1,422 mm, it can grow on the beach with tidal overwash. Wiggins also mentions that Brandegee noted that in the Cape region, this mangrove associate thrived on saline soil beyond the reach of the tide [16]. This variability in occurrence illustrates the importance of considering the combined effects of temperature, rainfall, drought intervals, and microtopography on the vulnerability of mangroves at their limits. Overall, our 1972/73 data show a decrease in height of the fringe mangroves from >4m to <1 m with latitude from c. 24 – 29 ^{o}N, as also reported more recently for the Baja Gulf Coast by Aburto-Oropeza et al.

Our precipitation (P_{mm}) and temperature (T) data (Figure 16) show there is a corresponding large decrease in P_{mm} along both coasts but the mean annual T varies little with latitude. Reef et al. emphasise the overall importance of nutrient availability on mangrove size and productivity for mangrove survival but there are few data for Baja California shrub mangroves [86]. A study of nutrients at four sites near La Paz, where P_{mm} and T are relatively high, shows that soil N and P are lowest in the temporarily flooded high marsh, where shrub heights are also lowest for *R.mangle*, *L. racemosa* and *A.germinans* [16]. At Puerto Lobos, a more detailed study was made of a semi-enclosed, microtidal site on the northern Sonora coast to measure the importance of tidal flow, elevation and range, rainfall, catchment size and litterfall on nutrient dynamics in *A. germinans* [87]. This study concluded that these parameters were not significantly related to mangrove cover at this semi-arid site where local environmental conditions (geoform and microtopography) were of primary importance. Gonzáles-Zamorano et al. considered that higher seasonal tides and temperatures on the steep-sided Gulf coast of Baja California imposed more stress on the wetland vegetation than on the west coast [27].

On the Pacific coast of Baja California, Acosta–Velázque and Ruiz-Luna found that at Bahía Magdalena, *R. mangle* and *L. racemosa* are common near drainage channels while *A. germinans*

occurs where flooding occurs at spring high tides a few times a year. As reported for the Abreojos and El Coyote case histories, the mangrove distribution in these long narrow Pacific lagoons is limited to areas of daily tidal exchange. Blocked channels result in prolonged flooding and lead to death of the shrubs and replacement with saltmarsh species *Batis maritima* and *Distichlis littoralis* with or without extremely stunted *R. mangle* with very small propafules (Figure 24). It is not clear if flood tolerance is separate from excess salinity and/or increased salinity range. The high marsh mudflats adjacent to Bahía Magdalena and Laguna San Ignacio are irregularly flooded by spring tides and by summer rain, with the salinity alternating between c. 40 – 60‰ and freshwater. During the dry seasons, the salinity may exceed 100‰ which is higher than the observed growth limits of Baja California mangroves around 45‰.

The location of the Baja California peninsula determines desert climatic conditions that are among the most extreme in the Northern Hemisphere for mangrove forest growth, exceeded only by the dwarf mangrove ecosystem of the Red Sea and Sinai Peninsula [13]. As discussed for hazards, it is expected that mangroves are most vulnerable at their climate limits. In 2005, the northern limits of the scrub mangrove forest in Baja California were reported as being at 26.7937 oN on the Pacific Coast, and at 29.04 ^{o}N for the peninsula Gulf Coast and the neighbouring Coronado Island [88]. *Rhizophora mangle* is the northernmost species on both coasts of Baja California; it occurs together with *Laguncularia racemosa* only on the Pacific Coast. These 2005 limits are the same as those observed in 1972/3. It should be noted that a record for red mangrove further north on Isla Ángel del la Guarda (at 29.19 ^{o}N) [47], cited by Glenn et al. and by González-Zamorano et al. (2011), is incorrect and refers to *Ruppia maritima* not *R. mangle* [24]. It is notable that on the Sonoran coast of the Gulf of California, *Avicennia germinans* grows further north — up to 31^{o} 15'N at Puerto Lobos (Cintrón-Molero and Schaeffer-Novelli, 1992), possibly having spread northwards from the location at 30^{o} 16'N reported by Felger and Lowe [40].

Our historical records suggest that there may have been some local changes in mangrove species ranges in Baja California, mostly on the Gulf Coast. The largest change seems to be the spread of *R. mangle* (*Rm*) from Bahía de Las Animas in 1921 to Bahía de los Angeles by 1964 [26,33]. Wiggins placed the northern limits of *L. racemosa* (Lr) and *A. germinans* (*Ag*) at Mulejé based on surveys up to 1971 but we found Ag at Ejido San Lucas 37 km further north in 1973 [16]. In 1988, Annetta Carter also collected Ag at Boca el Mojón (27.02 ^{o}N, -112.01 ^{o}W) between San Lucas and Mulejé, and around 1995, González-Zamorano et al. found it north of Sta. Rosalia at Bahía de San Rafael (28.452^{o}N, -112.982^{o}W) [51]. Field work of Yensen et al. set the limit of both Ag and Lr at Sta. Rosalia 13 km north of San Lucas in 1979 [44]. Felger and Lowe made a generalised statement about mangrove scrub with *Rm*, *Lr* and *Ag* occurring from La Paz to Bahía Las Animas but it is not clear that they found all these taxa at the northern limit [40]. Glenn et al. also listed *Ag* for Bahía de los Angeles and Las Animas but the basis for their determinations was not given and they may have been citing the work of Felger and Lowe. Overall, the historical data suggest there has been a northward migration of >100 km in *Ag* and *Lr* on the Gulf Coast during the past 44 years compared to <25 km for *Rm* [24].

In contrast, on the Pacific Coast, although *Ag* has expanded inland in parts of Bahía Magdalena, *Conocarpus erectus* is the only mangrove that shows a northward expansion. In 1973 it occurred at 25.74^{o} N, 122 km north of 24.63^{o} N where it occurred in c. 1988. León-de la Luz and Domínges-Cadena attributed the local growth and spread of Ce in the Cape region to increased El Niño-associated rainfall since c. 1986 [83].

The uneven distributions of *R. mangle* and *A. germinans* on the coasts of Baja California and Sonora seem to point towards differences in species vulnerability and hence in their limiting growth factors. However, genetic profiles suggest that *Ag* is a relatively recent (Post-Glacial?) immigrant to the west coast of Baja California whereas Rm has been established in the Cape for several millennia [89]. Earlier colonization of *Rm* due to a more effective dispersal capability can explain its higher genetic admixture but an earlier arrival does not account for the genetic structure found in both *Rm* and *Ag*. Sandoval-Castro et al. therefore consider that topography and propagule dispersal may be additional factors that impose greater limits on spread of *Ag* along the unevenly rocky Gulf coast compared to the lower-lying, sandier Sonoran coast. *Rm* spreads by vivipary and has propagules resistant to months of seawater inundation whereas *Ag* and *Rm* are clonal and its propagules are less buoyant and less resistant to prolonged emersion. *Rm* is also more tolerant of changes in wetland hydroperiod and it has a longer flowering period and more robust propagules that can survive the dry season when the water level is low and the salinity is maximum (Domínguez- Cadena et al., 2016). However, Sandoval-Castro et al. comment that the parental cost is higher for *Ag* and *Rm* than for *Lr* because the latter species responds faster to changes in humidity and flooding [89].

Mangrove distributions are generally considered to be controlled by ocean and air temperatures, with limits corresponding to the 20 – 24^{o}C and 5^{o}C, respectively. At their limits the Baja California peninsula, however, ocean water temperature is 18 – 22^{o}C on the Pacific Coast and c. 18 – 29^{o}C on the Gulf Coast. Global climate warming might therefore be expected to favor survival of the dwarf mangroves at their northern limits. Growth experiments with *Ag* and *Lr* seedlings in San Diego (32.5°N) in 1963 showed that *Lr* survived for several years until killed after several years with diurnal minima below freezing [90]. In fact, the New Zealand species *Avicennia marina* introduced in 1968 has become a harmful species requiring periodic eradication. Comparison of climate data from 1975 (Figure 15) and 2017 shows that at Laguna Abreojos, there has been almost no change in average annual temperature but there is an increase in the the warmest month from c. 27 to 35^{o}C and a corresponding decrease in minimum monthly average from c. 17 to 9.3^{o}C [74]. Average annual rainfall has increased from 76.8 to 80 mm. At Bahía de los Ángeles, corresponding average changes are an increase in maximum from c. 30 to 36.1^{o}C, a drop in minimum from c. 16 to 9.4^{o}C, and a slight rainfall decrease from 73.6 to 72.9 mm. The most severe minima at both sites are well above the threshold values of −6.3 to −7.6°C established by Osland et al. for *A. germinans* survival in Mississippi [91].

The combined temperature and precipitation increases at Abreojos might be expected to favor mangrove growth and northward migration. Furthermore, ocean surface water (0 to 100 m) off San Diego has become warmer than a century ago, and it is speculated that the shrub mangroves may migrate northwards as in the mid-Holocene warm interval when pollen data show that R [92]. *mangle* and *L. racemosa* were present near San Diego [13]. The absence of *A. germinans* pollen seems to reflect the greater vulnerability of small black mangrove trees to extreme winter climate changes although the seedlings are less sensitive [93]. The data in Figure 18 suggest that a mean annual T of 21^{o}C determines

the limit of co-occurrence of *R. mangle* and *A. germinans* in Baja California. Northward migration of mangrove propagules, however, would require coastal currents that flowed north around the rocky Viscaino Peninsula where there are no tidal wetlands, transporting them to sandy areas in Zones I and II (Figure 2). On this coast, the nearshore current direction is predominantly southwards. However, Zaitsev et al. show there can be a poleward advection current during autumn that transports subtropical waters northwards along the west coast [59]. This type of water mass intrusion is more intense during El Niño years when there is also intensification of upwelling events that deliver higher nutrient water onshore.

It has been predicted that more violent storms, flash floods and more frequent droughts will characterise the Baja California peninsula in the future [22,94]. Air temperatures are expected to rise c. 2º C with continued rates of CO_2 increase. The rising tropical water temperatures will also drive more frequent El Niño events associated with stormy weather [23]. It is known that recurrent storms and drought cycles have a major impact on forest mangroves in SW Florida, Puerto Rico, the Caribbean and Guayana [32,95,96]. However, there is little published information on the importance of these factors for scrub mangroves at the northern limits of their distribution despite ongoing investigations at the Smithsonian Institution and University of California Los Angeles. It is presently unclear to what extent increased sea level rise, upwelling and storm wave transport of nutrients to the Pacific lagoons may account for the observed height increase of the dwarf mangroves at their limits versus the potentially adverse effects of nitrogen enrichments and shoot:root growth stimulation that can result in shoot damage and reduced growth [97]. On the Central Gulf Coast, past periods of higher rainfall in Zone V are associated with increased flooding, channel movement and expansion of river fans that could accommodate more mangrove growth [81]. However, the modern practice of levee construction would prevent these natural changes and possibly intensify erosion of the mudflat habitats that accommodate the remaining mangroves.

Also, although the Gulf waters have warmed over the past fifty years, Lluch-Cota et al. found no significant sustained long-term trend in variables such as sea level rise and upwelling because the variability was dominated by interactions of ENSO and the Pacific Decal Oscillation (PDO).

Management

Several recent papers review the challenges of mangrove preservation and forest management in Baja California, and there is little that the 1972/73 study can add to these perspectives [49]. In general, the government of Mexico and its Baja Peninsula states have been aware of the need for preservation of their mangrove resources since 1974 when the Ramsar Convention of global inter- governmental wetlands protection came into effect. The first responses were the creation of the El Vizcaíno Biosphere Preserve and the marine preserves for Bahía de los Ángeles and Loreto with the intention of conserving resources by defining protected areas. However, the conservation areas also permit sustainable use of natural resources, and regulation of this usage was often weak. Furthermore, in 2004, the Mexican federal government substantially relaxed legal protection of mangroves in lieu of a fee or monetary compensation and the Gulf Coast biological reserves suffer from lack of policy implementation and law enforcement [48].

After the decentralisation of environmental control shifted from the federal to state level in 1992, the problem of management and implementation of dry coastal vegetation resource protection in Baja California received more attention and papers therein) [15]. A broad plan of coastal management was formulated which is grounded in research and ecologically-sensitive ecotourism, farming and urbanisation, public education, and regional research on mangroves is evident in the rise of published papers (Figure 3). However, the case histories for the Loreto-Nopoló area and La Ribera illustrates the difficulties in implementing truly sustainable development without a system for rigorous monitoring of coastline use and without binding legislation to prohibit unsuitable developments. The Villages of Loreto project initially resulted in over-development and depletion of water resources, resulting in financial failure. Subsequent partnership with non-governmental (NGO) businesses that invested in ecotourism has been more successful but uncontrolled expansion of this model may take its toll of pocket mangroves of Zone V. Most of the reviews on management of mangrove woodland in Baja California conclude that the forests remain threatened on the Gulf Coast, in the Cape (see La Ribera study in Sect. 4.2.1.1) and in the Bahía Magdalena area where there is pressure for increased channel dredging to allowing entry of larger ships ships more tourism [71]. There are also plans for expanded aqua-culture (shrimp farms and aquatic clam farms) that will need co-ordination as polyculture industries within restricted areas that minimise mangrove impacts [98].

It is usually considered that the Pacific Coast of Baja California is less impacted than the Gulf Coast and of lower concern for management regulation. Interviews of native residents and stakeholders found the general view was that sea-level rise and shoreline erosion were the main threat to mangroves on this coast [15]. However, Young points to significant problems within the El Vizcaíno Biosphere Reserve, particularly the Laguna San Ignacio area [66]. Here it local participation in conservation endeavors is both critically important and highly problematic. Despite its preserve status, the El Vizcaíno Biosphere Reserve failed to translate community-based conservation rhetoric into hands-on protection efforts, leading to poaching of scallops, abalone, and sea turtles, and other illegal activities like drug trading.

Young describes subsequent efforts to strengthen local participation in conservation through collaboration among field staff, area residents and NGO, such as ProNatura and the Lga. San Ignacio Ecosystem Science Program [66]. The ProNatura consortium aims at protection of a coastal wetland complex covering 570 km^2 through 33 conservation agreements and education programs. Results are variable with some mangrove losses in southern sectors of Lga. San Ignacio but with increases in the Abreojos and El Coyote lagoons that are attributed to protection by the fishing co-operatives [94]. Overall, however, area residents have negative views of future trends of mangroves and the fisheries resources they support [94]. This pessimism is based on observed damage from rising sea-level, storms uprooting or burying mangroves, rising water temperature and increased outbreaks of red tides, and leaf burn during dry periods. These factors are beyond the arena of woodland resource management and underscore the importance of continued studies of mangrove and seagrass propagation and transplant experiments as for the Nopoló area (Sect. 5.2.4) and also successful at La Paz and B. Magdalena [99-109].

Conclusion

Despite the small height (<1–4 m) of the transitional dwarf/scrub mangroves in Baja California north of the Cape Region, new studies have shown that that these semi-arid "dryland forests" play a vital role in Earth's CO_2 sequestration and heat balance,

comparable that of large tropical forest trees. The acceleration of global warming on land and ocean since c. 1980 would be expected to favor mangrove production by 1) northward spread of dwarf forest, 2) local areal expansion, and 3) increased cover height. However, on the Baja California Peninsula, there have been counteractive forces promoted by increased highway access and tourist population growth after 1974 m. These anthropogenic changes have severely reduced local mangrove extent despite the warnings represented by failed development projects, e.g., at La Ribera in the Cape Region. Furthermore, ocean warming favors increased severe storminess that negatively impacts dwarf mangrove forests, particularly on the Pacific Coast.

An extensive review of the history of study on the BCS dwarf mangroves includes data from the diaries and collections of the earliest botanical explorers in the field work from c. 1830 up to modern (2019) remote-sensing surveys. These background data provide a general baseline for estimating the changes in the extent and health of the Baja California Sur transitional dwarf scrub mangroves over the past c. 200 years. In addition, previously unpublished data from 42 sites surveyed in 1972 – 1973 and seven detailed case histories provide ground-truthing for satellite imagery that often over-estimates scrub mangrove coverage, mistaking saltmarsh shrubs for scrub mangrove. The combined floristic data show that in the more remote, unpopulated northern Gulf Coast Region VI, there has been a small northward expansion of Rhizophora mangle to Estero La Mona (28.89° N) on the coast of Bahía de Los Ángeles since 1921 but no more northerly expansion on the Baha Peninsula in except offshore on southern Isla Smith (a.k.a Is. Coronado, 29.047° N). There are also large areal and height increases of dwarf mangroves at Bahia Animas, and Avicennia germinans has migrated northwards by about 1o latitude in northern Zone V. Southwards in central Zone V, land clearance and increased frequency of flooding from the time of Missionary settlement in the early 1770's have locally reduced the forest by at least 75%, and there are no longer mangroves 4 to 7 m-high. Since 1974, however, there have been some area-wide and height increases of dwarf mangrove shrubs within areas now in ecosystem preserves. On the Pacific Coast, the only mangrove species expansions appear to be in Conocarpus erectus from 24.6 to 25.7° N, and the inland spread of A. germinans inland at Magdalena Bay. On this coast, significant anthropogenic impacts have been primarily associated with construction, land clearance and cannery wastewater discharge in the Magdalena Bay region. Locally, there was an annual deforestation loss of c. 4% for San Ignacio Lagoon from 1990 to 2005.

Studies of the floristic distributions of 63 wetland species in 1973/74 show that tidal wetland species diversity (N) is slightly lower (N = 10 – 20) on the arid Gulf Coast than the Pacific Coast (N = 13 – 27), and salt-marsh diversity is greatest in the latitudes above 29° N where the mangroves disappear. There was c. 50% decline in diversity with rainfall decrease within both the barrier lagoon and estuarine geo-forms. All barrier lagoons (young or mature) supported a lower diversity than the estuaries but the estuarine wetland species showed greater sensitivity to annual precipitation, as expected for environments shaped by river runoff. On the Pacific coast, the fewest species were associated with the precipitation minimum of 49.9 mm. Soil salinity data show that the mangrove shrubs had a lower range of soil salinities (0.5–45‰) than herbaceous taxa (20–90‰). Maximum % abundance for R. mangle and A. germinans occurred at 35‰. Lower values were found for the maximum % abundances of L. racemosa and Maytenus, and the lowest soil salinity maximum of 2‰ occurred with C. erectus.

A Venn plot of mean annual temperature (T_{ann}) vs. precipitation (Pann) shows that the Baja Peninsula mangroves are confined to regions with T_{ann} >20 °C. However, only saltmarsh taxa occur within the driest and warmest sector (c. 23 – 25°C, Zone VI, although there is one single site with A. germinans in this zone at Puerto Lobos, Sonoran Mexico. In the slightly moister Gulf sector of Zone V, Ag occurs alone at Sta. Rosalita but elsewhere the tidal wetlands include either Rm + Ag or Rm+ Lr. The wettest Gulf sector (Zone IV) also had Rm + Ag. In the driest sectors of the cooler Pacific Coast Zone III with T_{ann} (20 – 22°C), Rm and Lr occur but Ag is absent north of San Jorje c. 25.7° N, and in 1973, Mp had its northern limit at San Gregorio c. 26.1° N. A mean annual T of 21°C determines the limit of co-occurrence of Rm and Ag in Baja California.

Historical deforestation losses for San Ignacio and the Bahía Magdalena-Almejas Lagoon complex have been primarily related to hurricane and drought events by Cota-Lucero et al. (2016). Our comparison of Baja Peninsula population growth versus frequency of tropical storms shows that a rise in storm frequency began around 1960, before the steep population increase that followed the 1974 TransPeninsula highway construction. At Punta Abreojos, storminess has doubled in frequency over the past decade whereas data from 1975 to 2017 show that there has been little change in annual rainfall and temperature (8oC increases of the warmest month counter a corresponding decrease in the coldest month). It is unclear how much rising sea level rise, increased upwelling and storm wave transport of nutrients to the Pacific dwarf mangrove habitats may account for the c. 1 m increase in canopy height at their limits versus the potentially adverse effects of nitrogen enrichments and shoot:root growth stimulation. Although there is potential for mangrove growth as far north as San Diego (c. 32.7° N), a combination of suitable coastal habitat and storms of sufficient strength to transport propagules northwards are required to realize this niche potential. A review of management methods to protect and increase Baja Penisula scrub mangrove growth shows that the federal-level creation of biosphere and marine preserves suffers from lack of strong usage regulation and law enforcement. State-level implementation of sustainable coastal development plans also lacks rigorous monitoring of coastline use and binding legislation. Locally regulated NGO conservation efforts on the Pacific coast have met some success when supported by fishing co-operatives but overall, area residents are pessimistic about the future trends of mangrove survival and the fisheries that they support.

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