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Coastal wetlands of the northern Gulf of California: inventory and conservation status

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ABSTRACT

1. Above 28°N, the coastline of the northern Gulf of California is indented at frequent intervals by negative or inverse estuaries that are saltier at their backs than at their mouths due to the lack of freshwater inflow. These 'esteros' total over 215 000 ha in area and encompass mangrove marshes below 29°N and saltgrass (*Distichlis palmeri*) marshes north of 29°N. An additional 6000 ha of freshwater and brackish wetlands are found in the Colorado River delta where fresh water enters the intertidal zone.

2. The mangrove marshes in the Gulf of California have been afforded some degree of protected status in Mexico, but the northern saltgrass esteros do not have priority conservation status and are increasingly becoming development targets for resorts, vacation homes and aquaculture sites.

3. We conducted an inventory of the marshes using aerial photography and satellite images, and evaluated the extent and type of development on each marsh. We reviewed the available literature on the marshes to document their vegetation types and ecological functions in the adjacent marine and terrestrial ecosystems.

4. Over 95% of the mangrove marshes have been developed for shrimp farming. However, the farms are built adjacent to, rather than in, the marshes, and the mangrove stands are still mostly intact.

5. The majority of saltgrass marshes above the mangrove line are still relatively unspoiled. However, resort and vacation home development is taking place on land surrounding them.

6. We recommend a system of protected reserves incorporating the pristine wetlands, along with water quality management and buffer zones for the more developed esteros. The saltgrass marshes should be considered for conservation protection, similar to the protection given to the southern mangrove marshes whose value has already been recognized.

KEY WORDS: estero; estuary; wetland; *Distichlis palmeri*; saltgrass; mangrove

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INTRODUCTION

The northern Gulf of California is a unique marine biome in the heart of the Sonoran Desert, with over 1200 km of desert coastline in the states of Sonora and Baja California in Mexico (Figure 1) (Alvarez-Borrego, 1983; Alvarez-Borrego and Lara-Lara, 1991; Felger and Broyles, 1997; Brusca, 2004; Brusca *et al.*, in press). The northern Gulf of California supports important commercial fisheries (e.g. Morales-Bojorquez and Lopez-Martinez, 1999; Sala *et al.*, 2004), as well as endemic and endangered species such as the vaquita porpoise (*Phocoena sinus*; Nava and Findley, 1994; Barlow *et al.*, 1997), the corvina-like totoaba fish (*Totoaba macdonaldi*; Cisneros-Mata *et al.*, 1995; D'Agrosa *et al.*, 2000), sea turtles (Alvarado and Figueroa, 1992; Seminoff *et al.*, 2003a,b; Felger *et al.*, 2004), sea lions (Le Boeuf *et al.*, 1983; Garcia-Rodríquez and Aurioles-Bambosa, 2004), whales (Breese and Tershy, 1993), and numerous species of waterbirds (Anderson, 1983; Evertt and Anderson, 1991; Palacios and Mellink, 1996, 2000; Mellink, 2001; Hinojosa-Huerta *et al.*, 2004). It is a key migration route for birds on the Pacific Flyway, providing a corridor of aquatic habitat across nearly 600 km of desert for species moving from South American

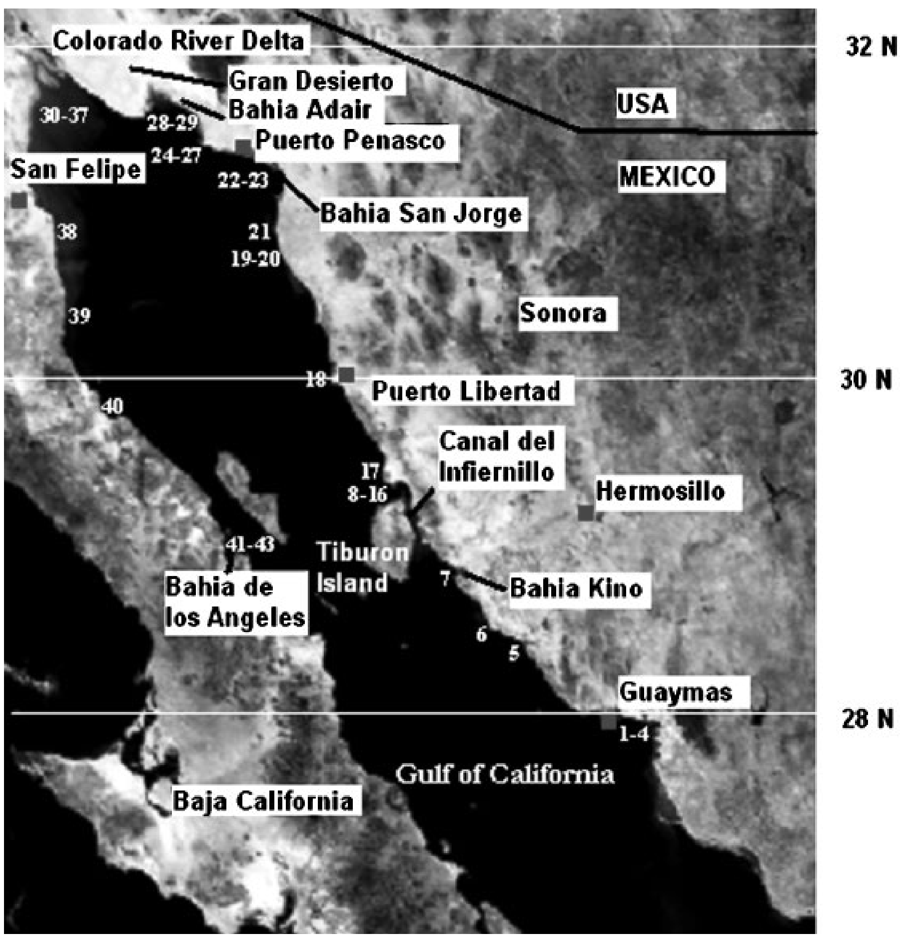

Figure 1. Locator map for the major esteros and other coastal wetlands in the northern Gulf of California. The background image is a 1990 Thematic Mapper satellite image.

wintering grounds to North American nesting areas (Anderson, 1983; Garcia-Hernandez *et al.*, 2001a; Hinojosa-Huerta *et al.*, 2004). Brusca *et al.* (2004) report 2802 marine species from the northern Gulf of California, including 2258 invertebrates, 367 fish, 146 sea birds, 24 marine mammals (cetaceans, pinnipeds, fishing bats), and seven reptiles (sea turtles, sea snakes).

Up to the 1940s the region was still nearly pristine (Steinbeck and Ricketts, 1941). Since then, however, the coastal zone has undergone increasingly rapid development and population growth (Almada-Bay, 2000), which in Sonora increased from 550 000 in 1950 to 2.3 million in 2000. Most of the coastal settlements are now linked to the major inland cities by paved roads and receive electricity from the national grid. Shrimp farms, salt ponds, electricity generating plants and resorts have also been built along the coast, and villages have expanded into small cities (Moreno, 1992; Almada-Bay, 2000). Guaymas, San Felipe, Puerto Peñasco and El Golfo now each support fleets of commercial trawlers and/or small-boat, artisanal fisheries, as well as extensive and growing resort developments. Much of the beach-front resort and residential development caters to US citizens who holiday or retire in Mexico. Some 10 million people now live within a few hundred kilometres of the head of the gulf in the USA and Mexico.

In the face of this rapid development, the health of the marine ecosystem is in question, the degradation of coastal habitats is already severe, and the esteros of the northern Gulf of California are undergoing rapid development (Brusca *et al.*, in press). Efforts are under way to protect the most important parts of the marine ecosystem and to regulate the fisheries so that they are sustainable over time. The value of the coastal rocky 'reef' habitat for marine life has been recognized, and a string of marine sanctuaries has been proposed (Sala *et al.*, 2002). The delta of the Colorado River, although much altered by upstream water diversions, is now protected in the Upper Gulf of California and Colorado River Delta Biosphere Reserve (Morales-Abril, 1994), but fishing restrictions are only weakly applied in the core and buffer zones (Cudney-Bueno and Turk-Boyer, 1998).

Although much of the shoreline is rocky or sandy, at frequent intervals the coast is indented with 'negative estuaries' (esteros) that tend to be saltier at their heads than at their mouths due to lack of freshwater inflow (Lavín *et al.*, 1998; Lavín and Sánchez, 1999; Brusca *et al.*, in press). These esteros are extensive in area due to the extreme tidal range of the northern Gulf of California (5–10 m amplitude) (Alvarez-Borrego, 1983). Most of the esteros are above the mangrove line (28–29°N) and are dominated by a low-growing saltgrass and herbaceous and shrubby halophytes (Felger, 2001; Brusca *et al.*, 2004, in press). Other coastal wetlands form where groundwater surfaces in springs near the coast or where agricultural drainage water is discharged into the intertidal zone (Glenn *et al.*, 1996, 2001).

Except for the Colorado River estuary (Glenn *et al.*, 2001), the wetlands of the northern Gulf of California have been little studied and have not become conservation targets. To the contrary, they have become primary sites for human development as resorts, marinas, salt works and shrimp farms. Although much of the estero land is federally owned (Steenblik, 1997), the government can grant concessions for development activities, such as aquaculture, in the esteros. Furthermore, some of the intertidal land was deeded in the past to individual ejidos (communal rural enterprises) for development of small-scale aquaculture. With passage of the 1992 land reforms in Mexico (Jones and Ward, 1998), the ejido lands have been privatized and can now be sold for private development of the land as resorts, vacation homes and marinas. Thus, the northern Gulf of California wetlands are under considerable development pressure.

This paper inventories this unique string of wetlands for the first time, documents the types of land conversion they are undergoing, and discusses their ecological roles in the adjacent marine and terrestrial ecosystems. It also makes recommendations for their conservation and management. The goal is to synthesize the available knowledge about these wetlands so that their potential conservation value can be recognized.

MATERIALS AND METHODS

Overview of methods

The study area includes the esteros and other coastal wetlands of the Gulf of California from Guaymas, Sonora (28°N), to the head of the gulf on the Sonora coast (32°N), and to Bahía de Los Angeles, Baja California (29°N) on the Baja California coast (Figure 1). This encompasses the northern limits of the mangrove zone on both coasts (Turner *et al*., 1995) and the saltgrass-dominated esteros above the mangrove zone (Brusca *et al*., in press). Aerial surveys were used to document human development in and around the wetlands, together with recent and archival Thematic Mapper (TM) satellite images to determine aerial coverage and changes within each wetland system over time. We reviewed the scientific literature, government reports, topographic maps and local knowledge to determine the composition and current status of the wetlands.

Vegetation surveys

Checklists of species were compiled at 16 wetlands during ground surveys conducted over the period 1983–2003 (Yensen *et al*., 1983; Zengel *et al*., 1995; Glenn *et al*., 1996; R.C. Brusca, pers. comm.), and additional species were added based on the literature and data from the Macrofauna Golfo Project (Brusca *et al*., in press). Tidal wetlands were divided into four zones with respect to tidal inundation: low, middle, high and supralittoral. Taxonomic designations and notes on distribution of species were based on Shreve and Wiggins (1964), Brusca (1980), Wiggins (1980), Yensen *et al*. (1983), Turner *et al*. (1995), Felger (2000, 2004), Brusca *et al*. (2004).

Aerial photography and satellite imagery

The coastline from Puerto Libertad to San Felipe was flown at approximately 500 m to 1000 m altitude on three flights in June and July 2003. The flight line was automatically recorded with a geographical position system (GPS). The aircraft was positioned just off the coast and a continuous record of the coastal wetlands and estuaries was recorded with a hand-held video camera. The video had a sound track that was used to note positions of each marsh and features of interest, including the extent of human development. Simultaneously, a photographic record of each wetland was acquired with a high-resolution film camera. Following the flight, a DVD with commentary was prepared, to aid in assembling the final list of wetlands. Colour slides were digitized then mosaicked to produce a high-resolution image of each wetland and its surrounding areas.

TM 5 satellite images taken in 1990 (30 m resolution) were mosaicked to form a single TM image of the northern Gulf of California (Figure 1). Each wetland was located on the TM and a geographical information system overlay of the perimeter was created and used to determine the size and exact location of the wetland. For most marshes, the perimeters were drawn to encompass the intertidal zone and lagoon within the marsh, including thickly vegetated areas and the sparsely vegetated salt flats at the backs. However, for the delta region of the Colorado River, only the vegetated parts of the extensive tide flats on the mainland and islands were included within the wetland perimeters. The vast areas of bare intertidal mud flats were excluded. Names of wetlands and other areas of interest were taken from the 1975 topographic series for Mexico (CETENAL, 1975). Some wetlands were not named on those maps; if they had local names, then these were included in our tables. Locations of wetlands in tables are given in Lat./Long. coordinates. A geospatial database was constructed, containing TM images, metadata, published literature, and current aerial photographs of each wetland (Nagler *et al*., in press). This database also contains checklists of vascular plants and invertebrates in the marshes.

Other satellite images were used for change detection. The coastline around Guaymas was viewed on TM images from 1973, 1983, 1990 and 2003. The delta of the Colorado River and associated wetlands were available on 1993–2002 annual images. Bahía Kino was covered on 1973, 1983 and 1990 TM images. Archival satellite images were acquired from the Arizona Regional Image Archive (Office of Arid Lands Studies, University of Arizona, Tucson, USA). Other images were obtained from EarthSat, Inc. (Rockville, MD, USA).

Assessment of human impact

Human impact was assessed on the basis of visual effects of development in and around the wetland area. Three primary types of human development were seen. First, many esteros support resorts and vacation homes, or local settlements (small towns, fishing camps). Second, some of the esteros have been developed for shrimp farming. Third, some of the esteros formerly had significant freshwater inflows that have now been diverted for agricultural development. These factors were considered in rating the wetlands on a scale of 0 to 3, where 0 represents no apparent human impacts, 1 represents some signs of human impact on the margins, 2 represents signs of moderate to heavy impact on the margins but the marsh system appears to be basically intact, and 3 represents greater than 50% of the wetland has been converted to alternate uses (ponds, marinas, resort development).

RESULTS

Inventory of wetlands

Forty-three major wetlands were identified in the study area (Figure 1, Tables 1 and 2), ranging in size from 5 ha to nearly 100 000 ha (the interconnected esteros of Bahía San Jorge). Numerous smaller wetland areas were observed and photographed, but these are not included in the tables. Total wetland area was 221 000 ha, of which 50 000 ha were mangrove marshes, 165 000 ha were saltgrass marshes, and 6000 ha were freshwater or brackish wetlands. Wetlands were much more extensive on the Sonoran coast (203 000 ha) than on the Baja coast (18 000 ha). Baja California is a steep, narrow peninsula with a predominantly rocky shoreline, whereas the Sonoran coast is less steep and has a predominantly sandy coastline that lends itself to the formation of salt marshes. The largest marshes are at the northern end of the study area, where the tidal amplitude is most extreme and where the shoreline has the shallowest slope, due to the deposition of sediment by the Colorado River.

Most of the esteros are of marine origin, formed by the action of tides and currents on coastal landforms. Small esteros form behind rocky headlands or sand spits, whereas very large esteros, such as those in Bahía San Jorge (Figure 2) and Bahía Adair, form at the backs of shallow bays. The backs of these tidal marshes are vast salt flats (salinas) created by the evaporation of seawater. Some of the marshes are of deltaic origin, formed at mouths of now-ephemeral rivers, including the Río Sonoyta (forming Estero Morua and Estero Pinta in Bahía San Jorge) and the Río Sonora (forming Estero Santa Cruz in Bahía Kino). The delta of the Río Asuncion (an extension of the Río San Miguel) ends behind a high strand of coastal dunes without forming a large delta, but groundwater comes to the surface behind the dunes, thus creating wetlands (Figure 3).

The only true estuary today is the intertidal zone of the Colorado River (Figure 4), since this is the only marsh that has a perennial inflow of river water (now made up mainly of agricultural drainage water except during flood years) (Glenn *et al.*, 1996). Since silt is now trapped in upstream reservoirs, the delta is diminishing in area rather than accreting (Carriquiry and Sánchez, 1999). Large slices of shoreline frequently calve into the currents in the final, intertidal part of the river as it approaches the north side of Isla Montague (Carriquiry and Sánchez, 1999). Hence, the marine zone is moving upstream. However, the

Table 1. Estuaries and other coastal wetlands of the Sonoran coast, from Estero Los Lobos to the mouth of the Colorado River

No.	Name	Latitude (° ′ ″ N)	Longitude (° ′ ″ W)	Area (ha)	Vegetation	Human impact[a]
1	Estero Lobos	110 31 42	27 31 21	22 527	Mangrove	(2) SF, D
2	Esteros del Río Yaqui	110 35 53	27 40 27	17 826	Mangrove	(2) D
3	Estero el Rancho	110 50 12	27 56 34	219	Mangrove	(3) SF, C, S
4	Estero Soldado	110 58 31	27 57 32	264	Mangrove	(1) R
5	Estero Tastiota	110 36 31	28 22 02	2428	Mangrove	(2) SF
6	Estero Cardonal	111 42 06	28 27 44	311	Mangrove	(2) SF
7	Estero Santa Cruz	111 52 58	28 46 54	3622	Mangrove	(2) SF, R, D
8	Estero Santa Rosa	112 09 21	28 58 07	210	Mangrove	(0)
9	No name	112 12 04	28 58 26	11	Mangrove	(0)
10	No name	112 11 52	29 00 39	42	Mangrove	(0)
11	Estero La Ona	112 11 35	29 09 41	19	Mangrove	(0)
12	Estero Viboras	112 16 01	29 10 43	36	Mangrove	(0)
13	Estero Arenas	112 13 28	19 11 06	189	Mangrove	(0)
14	No name	112 16 04	29 10 46	10	Mangrove	(0)
15	Estero la Perla	112 17 09	29 13 25	116	Mangrove	(0)
16	Estero Sargento	112 19 08	29 20 00	1235	Mangrove	(0)
17	Puerto Libertad	112 41 35	29 54 31	0	None	(3) C
18	Puerto Lobos	112 51 26	30 16 16	4	Halophyte marsh with a few black mangroves	(2) S
19	Estero Los Tanques	112 52 43	30 26 51	543	Halophyte marsh	(0)
20	Delta del Río Asuncion	112 59 19	30 33 21	9233	Mesquites and halophytes behind dune line where river approaches coast	(2) D
21	Estero de San Francisco	113 05 42	30 56 28	543	Halophyte marsh	(0)
22	Esteros de Bahía San Jorge (Salina & Almejas)	113 03 54	31 09 08	98 740	Halophyte marsh with salt flats at back	(1) S

23	Estero La Pinta	113 14 51	31 15 52	3338	Halophyte marsh	(2) R, C
24	Estero Morua	113 26 19	31 17 09	1097	Halophyte marsh	(2) R, C, S
25	Puerto Penasco	113 32 59	31 18 24	0	None	(3) C, S
26	Estero La Cholla	113 36 35	31 20 48	235	Halophyte marsh	(3) C, R
27	Estero Cerro Prieto	113 37 12	31 25 31	1987	Halophyte marsh	(1) S
28	Esteros de la Bahía Adair	113 56 15	31 35 54	29 226	Extensive halophyte marsh system with salt flats at back	(0)
29	La Salina	114 07 50	31 31 22	398	A cut off salt flat with vegetated upwellings (pozos) around edges	(1) S
30	El Golfo de Santa Clara	114 30 02	31 41 14	0	None	(3) C, R, S
31	El Doctor pozos	114 45 27	31 57 35	1178	Brackish and freshwater upwellings supporting emergent marsh plants, shrubs and trees	(2) S, SF
32	Cienega de Santa Clara	114 52 55	32 01 39	4477	*Typha domengensis* (cattail) marsh	(1) S
33	Isla Montague	114 45 25	31 45 11	1209	*Distichlis palmeri* (saltgrass) marsh	(2) D
34	Colorado River tidal marsh, Baja side	114 49 00	331 45 50	1661	*Distichlis palmeri* marsh	(2) D
35	Colorado River tidal marsh, Sonora side	114 46 41	31 49 03	139	*Distichlis palmeri* marsh	(2) D
	Total area			203 072		

[a] The extent of human impact on each wetland was rated from 0 to 3: 0 is no apparent impact; 1 is some human impact evident but the wetland appears intact; 2 is the wetland has been altered by reduced freshwater flows, extensive resort development or aquaculture, but appears mostly intact; 3 is >50% of the wetland has been converted to other uses. Codes for types of development: shrimp farms on margins of the marsh (SF); resort and vacation homes on margins (R); local settlements on margins (S); diversion of freshwater flows from rivers (D); and clearing of marsh area for development (C).

Table 2. Coastal estuaries of the Baja California coast in the Gulf of California, from the delta of the Colorado River to Bahía de Los Angeles

No.	Name	Latitude (° ′ ″ N)	Longitude (° ′ ″ W)	Area (ha)	Vegetation	Human impact[a]
36	Salinas de Ometepec	114 58 12	31 36 39	1616	Halophyte marsh	(0)
37	Esteros de la Bolsa	114 53 35	31 16 59	15 660	Halophyte marsh	(2) SF, R
38	San Felipe	114 49 47	31 02 13	0	Halophyte marsh	(3) C, R
39	Esteros Percebu and Aztecu	114 42 05	30 45 53	738	Halophyte marsh	(1) R
40	Estero Bahía San Luis Gonzaga	114 24 18	29 48 31	189	Halophyte marsh	(1) R
41	Bahía de Los Angeles	113 29 18	28 53 18	145	Halophyte marsh with some black mangroves	(1) R
42	Estero La Mona	113 29 16	28 53 19	110	Halophyte marsh with mangroves (?)	(0)
43	Estero Los Animas	113 18 47	28 48 02	55	Halophyte marsh with some black mangroves	(0)
Total area				18 513		

[a] The extent of human impact on each wetland was rated from 0 to 3: 0 is no apparent impact; 1 is some human impact evident but the wetland appears intact; 2 is the wetland has been altered by reduced freshwater flows, extensive resort development or aquaculture, but appears mostly intact; 3 is > 50% of the wetland has been converted to other uses. Codes for types of development: shrimp farms on margins of the marsh (SF); resort and vacation homes on margins (R); local settlements on margins (S); diversion of freshwater flows from rivers (D); and clearing of marsh area for development (C).

Figure 2. Estero Almejas, one of the large interconnected esteros in Bahía San Jorge in the northern Gulf of California. The darker vegetation on the sand bars at the mouth of the estero are beds of the grass *Distichlis palmeri*. The lighter vegetation is the mixed halophyte community in the mid zone. The back of the estero is covered with salt flats.

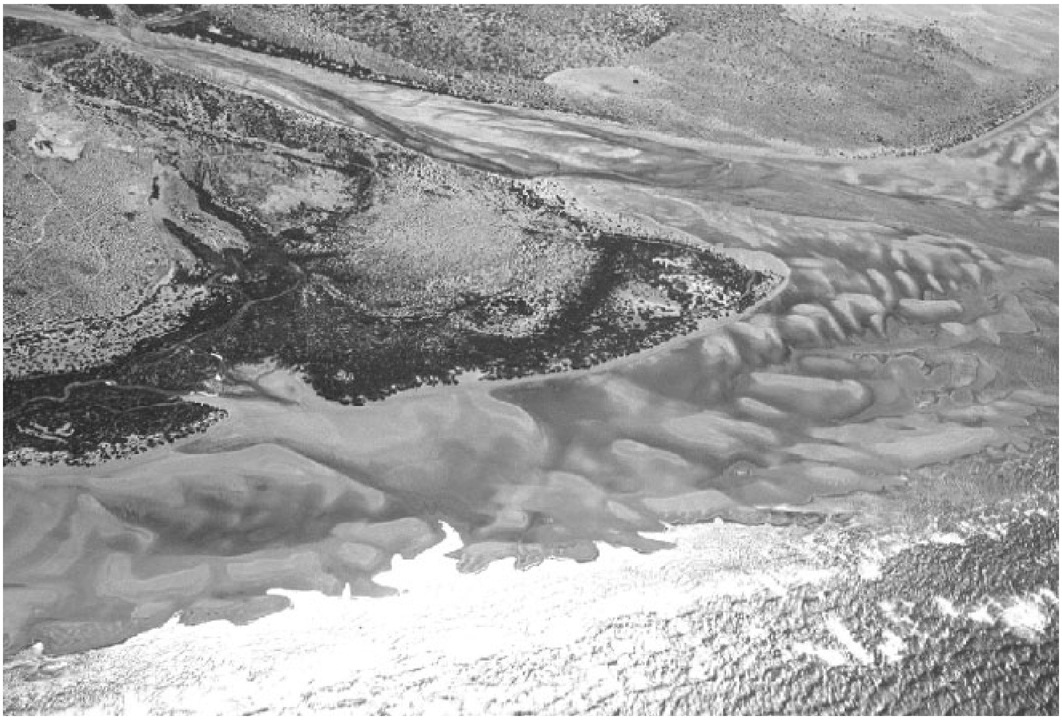

Figure 3. The delta of the Río Asunción in the northern Gulf of California. Owing to upstream diversions for agriculture there is no surface flow in the river as it approaches the sea. However, groundwater surfaces near the coast, creating a vegetated zone behind the dune line. Vegetation consists of halophytes and mesquite trees.

estuary is still turbid due to resuspension of sediments by the tides (Carriquiry and Sánchez, 1999) and is not considered to be nutrient limited (Hernandez-Ayon *et al.*, 1993). The delta supports the greatest diversity of wetland types found in the northern Gulf of California, including saltgrass marshes, cattail marshes, pozos and a riparian corridor containing native *Populus fremontii* (cottonwood) and *Salix gooddingii* (willow) trees (Glenn *et al.*, 2001).

Although they have been called negative or inverse estuaries, or esteros (Lavín *et al.*, 1998), many of the salt marshes have some freshwater influence. This is an important consideration in assessing their ability to support plants, because the range of plants that can grow in perpetually undiluted seawater is limited (Felger, 2000). Many are set in sand dunes that rapidly infiltrate rain water. The infiltrated water forms an aquifer that can be perched above seawater at the foot of the dunes where they encroach on the back of the marsh. Deeply rooted shrubs can root into this groundwater. For this reason, the high zone and supralittoral are often the most thickly vegetated parts of the marsh and may contain less-salt-tolerant plants that do not penetrate into the open marsh. Marshes at the mouths of ephemeral rivers usually have fresh or brackish aquifers that surface where the river approaches the coast or back of the marsh system. The Río Asuncion is thickly vegetated behind the foredunes on the coast, and Estero Morua and Estero Pinta support brackish vegetation where the Río Sonoyta riverbed reaches the coast between the mouths of the two esteros. Since the filling of Lake Powell in 1981, the Colorado River has carried substantial flows of fresh water to the Gulf of California in half the years, totalling about 20% of total river flows (Glenn *et al.*, 1996, 2001).

Non-tidal coastal wetlands are created around freshwater springs where subsurface water discharges near, or into, the intertidal zone, especially along the eastern escarpment of the delta region and near Bahía

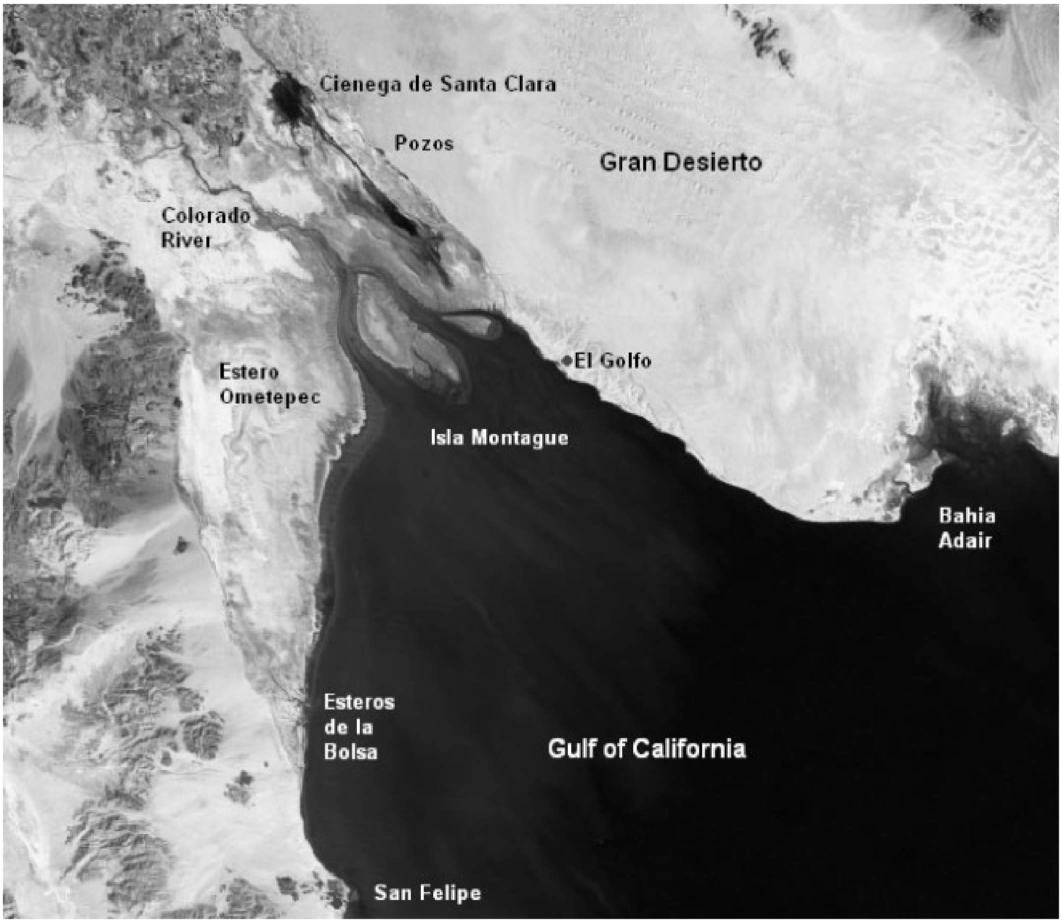

Figure 4. Major wetland areas of the Colorado River delta, shown on a 1990 Thematic Mapper satellite image.

Adair (Felger, 1980, 2000; Zengel *et al*., 1995; Brusca, 2002; Brusca *et al*., 2004). These 'pozos' (natural wells) are apparently fed by water that collects under the dunes of the Gran Desierto as run-off from the Pinacate, and flows towards the sea (Figure 5), or perhaps from even further away, north of the US–Mexican border (Brusca *et al*., 2004). Most of these pozos emerge onto salt flats as freshwater springs. Along the delta's eastern escarpment, between the intertidal zone and the Gran Desierto, the El Doctor pozos discharge into sand and form freshwater, pocket wetlands. The largest non-tidal wetland is Ciénega de Santa Clara (see Figure 4), an anthropogenic brackish marsh formed by the discharge of agricultural drainage water (3000 ppm total dissolved solids) from the USA into the eastern part of the Colorado River delta (Glenn *et al*., 1992, 1996; Zengel *et al*., 1995; Zengel and Glenn, 1996). Although they occupy only 6000 ha, the freshwater and brackish emergent marshes provide critical habitat for resident and migratory terrestrial birds and waterfowl (Garcia-Hernandez *et al*., 2001a).

Vegetation distribution

Lists of plant species are in Tables 3–5, divided into intertidal salt marsh species, species from the supralittoral zone of salt marshes, and species from non-tidal, fresh or brackish water marshes and pozos.

Figure 5. Pozos (springs), forming an interconnected strand of wetlands along the eastern escarpment of the Gran Desierto where it intersects the intertidal zone of the Colorado River delta. Plants include emergent species, shrubs (e.g. saltcedar) and trees (mesquites).

Table 3. List of vascular plants of the intertidal zone in northern Gulf of California esteros. The table indicates zonation within the marsh. Status of the plant as native or endemic is indicated

Mangroves
Avicenniaceae
Avicennia germinans (black mangrove), native, mid zone
Rhizophoraceae
Rhizophora mangle (red mangrove), native, low zone
Combretaceae
Laguncularia racemosa (white mangrove), native, high zone
Conocarpus erecta (button mangrove), native, high zone or supralittoral
Halophyte salt marsh community
Aizoaceae
Sesuvium verrucossum (western sea purslane), native, mid zone
Sessuvium portulacastrum (sea purslane), native, mid zone
Batidaeceae
Batis maritima (saltwort), native, low and mid zones
Convolvulaceae
Cressa truxillensis (alkali weed), native, mid zone and surpralittoral
Frankeniaceae
Frankenia salina (alkali heath), native, mid zone
Poaceae (grasses)
Distichlis palmeri (Palmer grass), endemic, low and mid zones
Monanthochloe littoralis (shore grass), native, mid zone
Sporobolus virginicus (beach grass), native, high zone and supralittoral
Chenopodiaceae
Allenrolfia occidentalis (iodine bush), native, high zone
Atriplex barclayana (coast saltbush), endemic, high and mid zones
Atriplex canescens var. *linearis* (narrow-leaf saltbush), endemic, high zone
Salicornia subterminalis, native, high and mid zones
Salicornia virginica, native, mid zone
Salicornia bigelovii (pickleweed), native, low and mid zones
Suaeda moquinii (desert seepweed), native, high zone and supralittoral
Suaeda esteroa, native, mid zone
Suaeda puertopenascoa, endemic, mid zone

Mangrove swamps form below 29°N, and saltgrass (*Distichlis palmeri*) marshes form above 29°N on both coasts (Turner *et al*., 1995) (Table 6).

All of the 20 intertidal plant species in the northern Gulf of California esteros are natives, and four species are endemic to the Sonoran Desert. The endemics include *D. palmeri*, a saltgrass that is only found in northern Gulf of California esteros. It produces a large grain that was harvested as a staple food by the Cucupa people in the delta of the Colorado River in the pre-dam era (Felger, 2000). Other endemics include a salt marsh succulent, *Suaeda puertopenascoa*, only found in the vicinity of Puerto Peñasco (Sonora, Mexico), and several endemic *Atriplex* spp. or varieties. In contrast to these esteros, nearby Pacific coast, southern California salt marshes have been extensively colonized by non-native species (Kuhn and Zedler, 1997).

On the other hand, the brackish wetlands in the delta of the Colorado River have been extensively colonized by introduced species. The salt-tolerant shrub *Tamarix ramosissima*, introduced to the southwestern USA in the 1900s, now dominates approximately 60 000 ha in the Colorado River delta (Glenn *et al*., 2001). In the delta region it extends from the freshwater, riparian corridor downriver nearly to the intertidal zone. It has spread south along the coast to Guaymas, occupying brackish niches in riparian

Table 4. Plants from the supralittoral zone, backs of esteros and adjacent dunes in the northern Gulf of California esteros. These are mostly halophytes or salt-tolerant glycophytes that grow above the high-tide line in freshwater or brackish soils. Some of them are also found within the marsh. The occurrence and growth form of each species is given

Nyctaginaceae
Abronia maritima (coastal sand verbena), native
Asteraceae
Ambrosia dumosa (white bursage), native
Baccharis emoryi, native
Chenopodiaceae
Atriplex barclayana (coast saltbush), endemic
Atriplex canescens var. *grandidentatum* (fourwing saltbush), endemic
Atriplex lentiformis (quailbush), native
Poaceae
Distichlis spicata (saltgrass), native
Jouvea pilosa (tropical beach grass), native
Frankeniaceae
Frankenia palmeri, native
Boraginaceae
Heliotropium curassavicum (alkali heliotrope), native
Lycium
Lycium andersonii (desert wolfberry), native
Lycium brevipes, native
Celastraceae
Maytensus phyllanthoides (mangle dulce), native
Cactaceae
Opuntia bigelovii var. *bigelovii* (teddybear cholla), native
Prosopis
Prosopis glandulosa var. *torreyana* (western honey mesquite), native
Prosopis pubescens (screwbean mesquite), native
Tamarix
Tamarix ramosissima (saltcedar), introduced
Typhaceae
Typha domengensis (southern cattail), native

zones and at the backs of esteros (Glenn and Nagler, in press). Other invasive, introduced species include *Rumex dentatus* (dock) and the annual grass *Polypogon monspeliensis*.

Human influences

The mangrove marshes and the saltgrass marshes are distinctly different in their degrees of human impact, as well as in the types of development pressure they face (Table 7).

Mangrove esteros

Over 95% of the mangrove marshes in the study area have been developed for shrimp aquaculture. As of May 2004, 115 shrimp farms had been built on the coast of Sonora alone, covering an area of 24 000 ha (Meling-López *et al*., 2004). Inspection of 1973, 1983, 1990 and 2003 TM images shows that nearly all the development has taken place after 1990 (Table 8). Some destruction of mangroves has been reported (Meling-López *et al*., 2004). However, in nearly all cases the shrimp farms have been located adjacent to, rather than within, the mangrove stands (Figure 6), and there has been little net loss of mangrove stands so far (Table 8; also see Páez-Osuna (2001) and Gonzalez *et al*. (2003)). This is due to federal legal restrictions

Table 5. Plants of Cienega de Santa Clara and the El Doctor and Bahía Adair Pozos. These marshes occur where brackish water or fresh water enters the intertidal or supralittoral zones. The soils become more saline away from the water source. The plants grow in fresh water, brackish water or highly saline water, depending on their position around the water source. (Plants of the Cienega and pozos that are already listed in tables for the intertidal or supralittoral zones are: *Sessuvium verucossum*, *Bacharis emoryi*, *Heliotropum curassavicum*, *Allenrolfia occidentalis*, *Atriplex canescens*, *Atriplex lentiformis*, *Salicornia subterminalis*, *Salicornia virginica*, *Suaeda moquinii*, *Cressa truxillensis*, *Prosopis glandulosa*, *Prosopis pubescens*, *Distichlis palmeri*, *Distichlis spicata*)

Apiaceae
Hydrocolyle verticullata (water pennywort), native
Asteraceae
Pluchea sericea (arrowweed), native
Pluchea odorata (alkali camphorweed), native
Chenopodiaceae
Nitrophila occidentalis (alkali weed), native
Cyperaceae
Cyperus laevigatus (flat sedge), native
Eleocharis geniculata (spike rush), native
Eleocharis rostellata (travelling spike rush), native
Scirpus americanus (bulrush), native
Scirpus maritimus (saltmarsh bulrush), native
Juncaceae
Juncus cooperi (spiny rush), native
Poaceae
Leptochloa uninervia (Mexican sprangletop), native
Phragmites australis (common reed), native
Polypogon monspeliensis (rabbitfoot grass), introduced
Sporobolus airoides (alkali sacaton), native
Polygonaceae
Rumex dentatus (dock, sorrel), introduced
Saururaceae
Animopsis californica (yerba mansa), native

Table 6. Plants found mainly north or south of 29°N along the coasts of the northern Gulf of California

Mainly north of 29°N
Frankenia salina
Distichlis palmeri
Monanthochloe littoralis
Atriplex canescens var. *linearis*
Suaeda moquinii
Suaeda puertopenascoa
Ambrosia dumosa
Atriplex canescens var. *grandidentatum*
Frankenia palmeri
Atriplex lentiformis
Tamarix ramosissima
Mainly south of 29°N
Avicennia germinans
Rhizophora mangle
Laguncularia racemosa
Conocarpus erecta
Sessuvium portulacastrum
Maytensus phyllanthoides

Table 7. Degree of human disturbance in mangrove and non-mangrove wetlands of the northern Gulf of California

Disturbance category[a]	Mangrove esteros (%)	Non-mangrove esteros and other wetlands (%)
0	3.9	17.8
1	0.8	62.4
2	94.8	19.7
3	0.5	0.1
Total area (ha)	49 371	172 204

[a] The extent of human impact on each wetland was rated from 0 to 3: 0 is no apparent impact; 1 is some human impact evident but the wetland appears intact; 2 is the wetland has been altered by reduced freshwater flows, extensive resort development or aquaculture, but appears mostly intact; 3 is > 50% of the wetland has been converted to other uses.

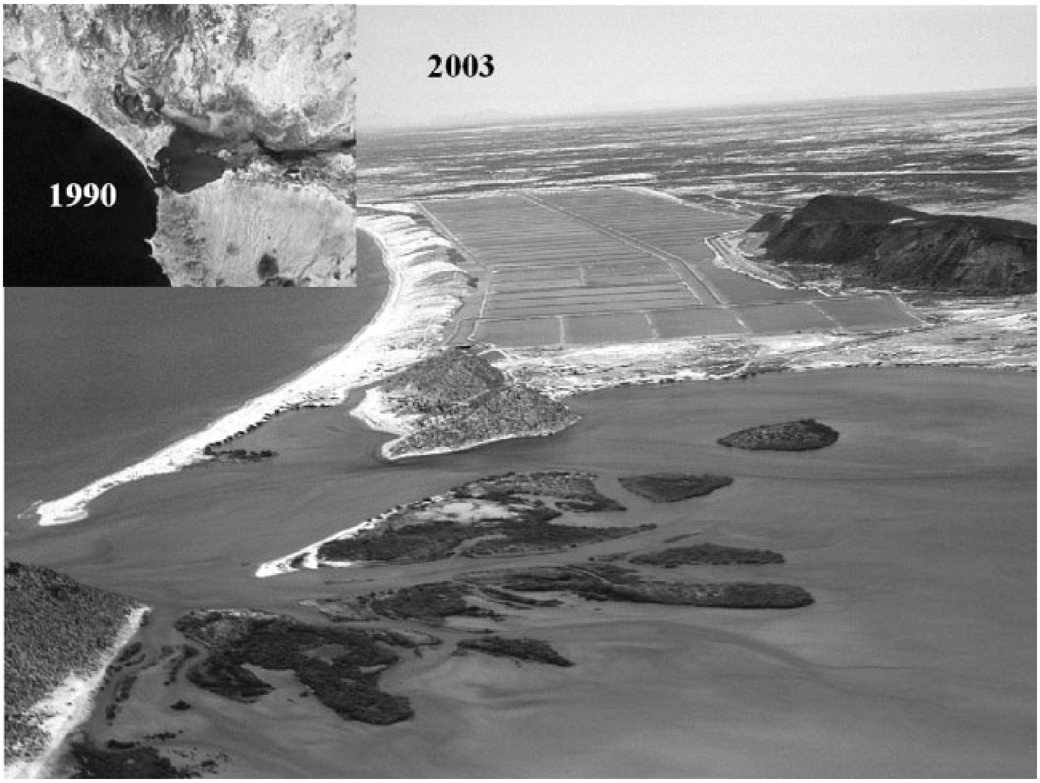

Figure 6. Tastiota estero in the northern Gulf of California in 2003, showing shrimp farm development. The inset is from a 1990 Thematic Mapper satellite image and it shows that the shrimp farms were placed on a former dry arm of the estero rather than in the vegetated portion of the estero.

on the clearing of mangrove forests, and also because pond construction and management are easier on the flats than in the mangrove marshes themselves. A similar development pattern has taken place in the mangrove esteros of southern Sonora, Sinoloa, and Nyarit (Páez-Osuna *et al*., 1997, 1998, 1999, 2002;

Páez-Osuna, 2001). The only significant mangrove esteros in the study area that have escaped development so far are in the Canal del Infiernillo between the Sonora mainland and Tiburon Island (nos 8–15 in Table 1), which is a protected homeland area for the Seri Indians. Near Guaymas, Estero Soldado also has a limited protected status through ongoing efforts of Conservation International, Mexico.

Mangrove esteros with shrimp ponds nearby have been damaged by several indirect impacts, including altered hydrological patterns, hypersalinity, and eutrophication (Páez-Osuna, 2001). The system of ponds, roads and levees at the back of the esteros reduces the ability of freshwater flows (rainfall, streams and springs) to penetrate to the intertidal zone. Furthermore, the sea water in aquaculture ponds induces sea water intrusion that raises the salinity at the backs of the marshes. As a result, the marsh may become hypersaline, reducing the vigour of the mangrove forests and in some cases leading to die-offs of white mangroves, which require some fresh water influence. In addition, eutrophication can occur through the discharge of shrimp pond effluent into the estero, or along the adjacent coastline. Eutrophication may not directly affect the mangroves, but it affects the periphyton and prop root communities at the base of the food chain, and the excess nutrients (and added chemicals and exotic pathogens) are discharged to the open sea (Páez-Osuna *et al.*, 1998, 1999, 2003). Esteros with shrimp farms, such as those at Guaymas and Kino Bay, have reportedly experienced increased incidences of red tide blooms and fish die-offs (Cortés-Altamirano *et al.*, 1996; Alonso-Rodríquez and Páez-Osuna, 2003). Hence, studies are needed on the ecosystem effects of shrimp farming on mangrove marshes and adjacent coasts.

Agricultural and municipal development have also impacted the mangrove marshes (Páez-Osuna, 2001). Upstream dams and water diversions for agriculture mean that the esteros of the Yaqui River delta (nos 1 and 2 in Table 1) no longer receive freshwater inflow. On the other hand, they do receive agricultural drainage water that is collected throughout the inland irrigation districts and discharged into the esteros via canals. They also receive municipal sewage discharge. These highly polluted waters contribute to eutrophication and introduce pesticides and industrial chemicals such as polychlorinated biphenyls (PCBs) and heavy metals (Páez-Osuna *et al.*, 2002). Mangrove esteros have been directly impacted where land has been cleared of mangroves for agricultural development (Páez-Osuna, 2001). Roads cut into the area around many esteros also destroy archaeological sites, such as shell middens and pre-Hispanic (aboriginal) camp sites.

Saltgrass esteros

In contrast to the mangrove esteros, over 80% of the estero area north of the mangrove line is still only lightly impacted by human development (Table 7). Shrimp farm development has been concentrated on the coastline south of Guaymas because the climate is warm enough to support two shrimp crops per year, compared with only one per year north of Guaymas. However, as the southern coastline has become overdeveloped, disease problems have resulted in reduced yields, and shrimp farming has moved north. At least two commercial shrimp farms of several hundred hectares each have been established at the head of the gulf near the towns of El Golfo and San Felipe. Unlike the case with mangrove marshes, shrimp farms can be placed directly in the saltgrass marshes, as there is currently no protection for this marsh type.

The main type of human impact on the saltgrass marshes to date has been tourist-related development of marinas, resorts and vacation homes. As with shrimp farms, in most cases the development occurs around the esteros rather than directly within them. In some cases, however, the esteros themselves have been converted, as at Estero Cholla north of Puerto Peñasco. Over 50% of this estero area has been drained and filled for resort development. In more lightly developed esteros, most of the development occurs along the dune line that typically separates the esteros from the open sea (Figure 7). The majority of resort and vacation home development is for US citizens, who visit the northern Gulf of California from southern Californian cities, as well as from Tucson and Phoenix in Arizona. The main issues associated with this type of development is pollution from sewage and grey-water discharge, and from off-road vehicle use. The beach communities are not connected to municipal sewage systems; hence, leakage of sewage through the

Figure 7. Estero La Pinta in the northern Gulf of California in 2003, showing extensive development of vacation homes on the coastal dune line in front of the estero.

dunes and into the esteros and the sea is likely. This effluent may present a human health hazard, and it may encourage the spread of introduced species, as has occurred in southern Californian marshes affected by freshwater inflow (Kuhn and Zedler, 1997).

Other wetlands

The Colorado River delta has suffered from a historic reduction in freshwater flows due to upstream water-diversion projects. A brackish clam (*Mulinia coloradoensis*) that was once abundant in the delta is now nearly extinct (Kowalewski *et al*., 2000; Rodríquez *et al*., 2001). From 1937 to 1964, very little river water reached the sea, as upstream impoundments behind the major dams (Hoover and Glen Canyon) were filling (Glenn *et al*., 1996). Since the impoundments first reached capacity in 1981, however, water has flowed to the sea during each major El Niño cycle, and these pulse floods have regenerated native trees in the riparian zone (Zamora-Arroyo *et al*., 2001) and stimulated the shrimp fishery in the upper gulf (Galindo-Bect *et al*., 2000). At the same time, discharge of agricultural drainage water has created new wetland areas, such as Cienega de Santa Clara and similar anthropogenic marshes. These wetlands support a rich diversity of birds (e.g. Hinojosa-Huerta *et al*., 2004) and fish species (e.g. Zengel and Glenn, 1996) and, so far, have not presented water quality problems for wildlife (Garcia-Hernandez *et al*., 2000, 2001b). In general, the wetlands of the Colorado River delta, although much diminished compared with pre-dam conditions, have improved over the past 20 years due to maturation of the dam system and to the discharge of agricultural drain water into the delta and intertidal zone (Glenn *et al*., 1996, 2001; Hinojosa-Huerta *et al*., 2004).

DISCUSSION

Ecological and economic importance of the wetlands

Strong food-web linkages have been demonstrated between North American salt marsh vegetation and nearshore fish consumers via detritus production and consumption. These systems include *Spartina alterniflora* marshes along the Atlantic and Gulf of Mexico coastlines (e.g. Darnell, 1961; Teal, 1962), the *S. foliosa* marshes of the Pacific Northwest (Naiman and Sibert, 1979), and California coastal wetlands (Kwak and Zedler, 1997). For example, the highly productive Atlantic menhaden (*Brevoortia tyrannus*) makes direct use of cellulose from *S. alterniflora* (Peters and Schaaf, 1981). In addition to the detritus from vascular plants, salt marshes fuel the food chain through production of eelgrass, macroalgae, phytoplankton and epiphytes.

No studies on primary productivity or food-chain dynamics have been reported for the esteros of the Gulf of California. However, similar marsh systems have been studied along the southern California coastline. Although the California marshes are sometimes considered to have low productivity with minimal input into the marine food chain, Kwak and Zedler (1997) demonstrated a strong salt marsh–channel linkage for the Tijuana estuary and San Deiguito lagoon. Vascular plant detritus and algae supported a variety of nearshore fish populations, as well as endangered birds and other biota. Based on these findings, they recommended that the estuary–nearshore channel habitats should be managed as a single ecosystem, and that restoration of intertidal marshes was compatible with enhancement of coastal fish populations, whereas previously they were considered to be competing objectives.

The extensive northern Gulf of California esteros are a nursery area for penaeid shrimp (Snyder-Conn and Brusca, 1977; Brusca, 2002; Calderon-Aguilera *et al*., 2003; Brusca *et al*., 2004) similar to the mangrove marshes to the south (Flores-Verdugo *et al*., 1993; Páez-Osuna *et al*., 1998; Whitmore *et al*., 2004). The commercial shrimp species spawn offshore and the post-larval stages migrate into the esteros to develop into juveniles (Calderon-Aguilera *et al*., 2003). Although the northern shrimp populations are adapted to hypersaline conditions (Calderon-Aguilera *et al*., 2003), Gallindo-Bect *et al*. (2000) found a positive correlation between freshwater flows in the Colorado River and the subsequent year's shrimp landings at San Felipe. They concluded that freshwater flows reduce the salinity in the Colorado River estuary, providing larval shrimp and perhaps some fish species protection from euryhaline predator fish.

The coastal wetlands of the gulf also play a critical role in the conservation of the avifauna of the Gulf of California and Sonoran Desert. These wetlands provide habitat for nearly 500 species of birds, many of them federally protected in Mexico, including clapper rails (*Rallus longirostris*), Virginia rails (*Rallus limicola*), least terns (*Sterna antillarum*), and western snowy plovers (*Charadrius alexandrinus nivosus*) (Russell and Monson, 1988; Brusca and Bryner, in press). These resident species depend upon the ecological integrity of these wetlands to survive. However, available information on their regional status and the effects of human activities on their populations is very limited.

Over 200 species of migratory bird have been documented along stopover sites in coastal Sonora alone (Patten *et al*., 2001), and large pulses of these birds are commonly observed during the peak of spring migration (Hinojosa-Huerta *et al*., 2004). It is likely that an important percentage of bird populations that breed in the western USA and Canada migrate through the coast of Sonora. The quality of stopover and wintering sites in migration routes has been identified as one of the most critical parameters defining the status and population trends of migratory birds (Rappole, 1995; Petit, 2000). Population declines have been linked to habitat loss and degradation of stopover sites in the USA, Mexico, and Central America (Hutto, 2000). Yet, there is almost no information on general patterns of geographic distribution, habitat quality, and avian use of stopover sites along the coast of western Mexico.

At the northern end of the Gulf of California, the wetlands of the delta of the Colorado River provide a variety of habitats that support a rich diversity of waterbirds, including, by one survey, 71 species of divers, waders, gulls, terns, skimmers, pelicans, cormorants, marshbirds, shorebirds and waterfowl (Hinojosa-Huerta *et al*., 2004). Montague Island alone supports breeding populations of 12 species of waterbirds in the *D. palmeri* beds. Over 160 000 shorebirds and tens of thousands of waterfowl use the delta as wintering grounds, making it one of the critical sites for migratory waterbirds on the Pacific Flyway (Hinojosa-Huerta *et al*., 2004). The delta appears to play an equally important role for migratory neotropical terrestrial birds, including threatened and endangered species (Garcia-Hernandez *et al*., 2001a). Very large numbers of these birds arrive at the delta during the spring migration season on their way to northern nesting areas.

Current conservation status

The wetlands at the head of the Gulf of California, including the large esteros of Bahía Adair and the Colorado River delta wetlands, are part of the Biosphere Reserve of the Upper Gulf of California and Delta of the Río Colorado (Morales-Abril, 1994; Brusca and Bryner, in press). This affords them some protection from development, although aquaculture and artinesial fisheries are still permitted. The mangrove marshes have some degree of protected status, as all four mangroves have been listed as rare and endangered species (Páez-Osuna, 2001). The remaining wetlands are, for the most part, unprotected. In particular, the saltgrass marshes do not have the same degree of protection as the mangrove marshes, and it is legally possible to clear the vegetation in these marshes for aquaculture or other uses. In the Gulf of California, rocky headlands and the southern mangrove esteros have been proposed for protection because of their demonstrated importance to the fisheries and to non-commercial species in the marine zone (Sala *et al*., 2002). By contrast, there have been few studies on the importance of the saltgrass esteros and they have not been proposed for special protection.

In Mexico, several federal agencies have responsibility for designating protected areas. These agencies include the National Institute of Ecology (Instituto Nacional de Ecologia), the National Commission on Natural Protected Areas (Comision Nacional de Areas Naturales Protegidas), and the National Commission for the Use and Study of Biodiversity (Comision Nacional para el Uso y Conocimiento de la Biodiversidad (CONABIO)). Priority conservation status for an area is awarded by CONABIO based on scientific studies documenting the importance of that habitat type in preserving and enhancing biodiversity, an important national goal. CONABIO acts as an information clearing-house for completed environmental studies. Hence, the northern gulf wetlands will not be considered for protection until their value in supporting biodiversity is documented. The present study is an attempt to begin the documentation process and to encourage research on the ecological values of these wetlands.

Our working hypothesis, based on the observations reported here, is that these esteros might have great, if unrecognized, importance to the marine food chain and to the movement of waterbirds and terrestrial neotropical birds along the desert coastline in the northern gulf. Based on our initial observations, the human impact on the esteros at current levels appear to be manageable. Aquaculture and tourism development has, for the most part, not taken place directly within the esteros, but adjacent to them.

Recommendations

As has been proposed for the southern Gulf of California rocky headlands and esteros (Sala *et al*., 2002), a system of protected reserves incorporating the pristine wetlands, along with water quality management and buffer zones for the more developed esteros, could preserve these wetlands for the future.

The still-pristine mangrove marshes along the Canal del Infiernillo between the Sonora mainland and Tiburon Island should become primary targets for protection in coastal reserves. This area also supports seagrass beds that are the base of a rich marine food chain (Meling-Lopez and Ibarra-Obando, 1999), and it is the homeland of the Seri Indians, who have so far not permitted aquaculture development in the esteros (Felger and Moser, 1985; Burckhalter, 2000).

Most of the remaining mangrove esteros have already been developed for shrimp aquaculture, but the mangrove stands are still largely intact. These esteros require initial water quality assessment, establishment of water quality standards for effluent discharge, establishment of operating standards to meet the water quality goals, and then monitoring to assure compliance (Páez-Osuna *et al*., 1998).

The saltgrass esteros of the northern gulf are not yet heavily influenced by human development. Hence, conservation efforts at this time could have profound and far-reaching positive impacts on the marine ecosystem of that region. Still-pristine or lightly impacted saltgrass esteros on the Sonoran coast include the estero complexes of Bahía San Jorge and Bahía Adair, covering 130 000 ha. These esteros, as well as the estuary of the Colorado River, appear to play important roles as feeding stations and nursery areas in the marine zone. They should be primary targets for protection within coastal reserves.

Many of the remaining saltgrass esteros have been moderately impacted by adjacent residential and resort developments. These esteros should be protected by prohibiting dredging or building within the intertidal zone, restricting off-road vehicle activities, and controlling the discharge of domestic sewage into the esteros. Of special concern are the developments built along the foredunes of these esteros. These typically rely on septic tanks to treat domestic sewage. These tanks discharge partially treated freshwater effluent into the dunes that presumably leaks into the esteros, introducing the possibility of eutrophication and the creation of areas of diluted salinity where introduced species can establish, as in Pacific coast marshes (Kuhn and Zedler, 1997). Golf courses, proposed for land adjacent to some of the esteros, would be another source of fresh water and nutrient runoff. The water quality problems associated with these esteros need to be identified, standards for discharge established, and monitoring programmes implemented. The Gulf of California saltgrass esteros may be especially susceptible to pollution because they currently receive little if any freshwater inflow, and have much less vegetation and, therefore, less capacity for absorbing nutrients than other coastal salt marshes.

The northern saltgrass marshes also need protection from development directly within the marsh. Unlike the mangrove marshes, it is still permissible to convert saltgrass marshes to shrimp ponds and marinas, or to fill them in for resort development. The saltgrass marshes should be given the same degree of protection as the mangrove marshes, as they fulfil many of the same ecological functions. Given the rapid population growth and economic development in the northern Gulf of California, an effective conservation policy must incorporate human aspirations into the planning process (Palmer *et al*., 2004). Research is needed to demonstrate the value of intact esteros to the commercial fisheries and tourist-related industries.

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